Geohydrology and Geochemistry Near Coastal Ground-Water-Discharge Areas of the Eastern Shore, Virginia

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Prepared in cooperation with the Accomack-Northampton Planning District Commission

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By GARY K. SPEIRAN

Prepared in cooperation with the Accomack-Northampton
Planning District Commission

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Flow	
inch per year (in/yr)	25.4	millimeter per year
gallon per minute (gal/min)	0.06308	liter per second

Water-quality units: Water temperature in degree Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the following equation:

$$°F = 1.8 \times (°C) + 32.$$

Chemical concentration is reported in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million. Specific electrical conductance of water is reported in microsiemens per centimeter at 25 degrees Celsius (µS/cm). Content in sediment is expressed as grams per kilogram (gm/kg).

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Geohydrology and Geochemistry Near Coastal Ground-Water-Discharge Areas of the Eastern Shore, Virginia

By Gary K. Speiran

Abstract

This report describes the results of a study of the effects of geohydrologic and geochemical processes on the discharge of nitrate in ground water in the surficial aquifer to coastal waters in, and near, areas of ground-water discharge on the Eastern Shore, Virginia. Nitrate in ground-water discharge is of concern on the Eastern Shore because elevated concentrations of nitrate contribute to the eutrophication of estuaries and because ground water that discharges from agricultural and residential areas can be significant sources of nitrate to these estuaries.

Geohydrologic and geochemical processes are affected by the grain size and the organic content of sediments that form the aquifers and the confining units through which ground water flows. These sediments form areally extensive formations for which regional patterns in grain size and organic content can be described, although local heterogeneities exist. The distribution in the grain size and the organic content of sediments results, in part, from the environment in which the sediments were deposited and are reflected in the topography, hydrology, and land use of today.

Sites were selected to evaluate the processes that predominate in four specific types of geohydrologic and geochemical environments. One site is located where precipitation that infiltrates through upland agricultural fields, recharges the surficial aquifer, and discharges to an estuary. This site is underlain primarily by fine-grained sediments that contain abundant organic material, but also is underlain by local deposits of coarse-grained sediments that contain little organic material near the estuary. A second site is located where precipitation infiltrates through upland agricultural fields, recharges the surficial aquifer, and discharges to an estuary. This site is underlain primarily by coarse-grained sediments that contain little organic material, but also is underlain by local deposits of fine-grained sediments that overlie the coarse-grained sediments adjacent to, and beneath, part of the estuary. The third site is located where precipitation infiltrates through upland agricultural fields, recharges the surficial aquifer, and discharges to a wooded wetland adjacent to a saltwater marsh. The upland fields are underlain by coarse-grained sediments that contain little organic material; the wooded wetland and marsh are underlain by a mixture of fine-grained and coarse-grained sediments that have varied organic content. A fourth site is located where precipitation infiltrates though upland agricultural fields, recharges the surficial aquifer, and discharges to a nontidal creek. The fields are underlain by coarse-grained sediments that contain little organic material; the flood plain of the creek is a riparian woodland and appears to be underlain by sediments that contain a mineral and organic content different from sediments that underlie the uplands.

In ground water recharged by precipitation that infiltrated through agricultural fields underlain by fine-grained sediments, the concentration of dissolved oxygen was less than 1 mg/L (milligrams per liter), and that of dissolved nitrate was less than the detectable concentration (0.05 mg/L

as nitrogen (N)). Rates of net ground-water recharge were less than 2 in/yr (inches per year) in these areas. In ground water from precipitation that infiltrated through agricultural fields underlain by coarse-grained sediments that contain little organic material and recharged the surficial aquifer, the concentration of dissolved oxygen generally exceeded 5 mg/L, and the concentration of dissolved nitrate commonly was 10 mg/L as N or greater. Rates of net ground-water recharge ranged from about 3 to 12 in/yr in these areas. Where ground water flowed directly from coarse-grained sediments toward an estuary, the concentrations of dissolved oxygen and nitrate changed little from that beneath the recharge areas. Where ground water flowed from coarse-grained upland sediments beneath riparian woodlands, concentrations of dissolved oxygen and nitrate were controlled predominantly by the organic material that was deposited when the sediments were deposited rather than by the presence of overlying riparian woodlands; concentrations of dissolved oxygen and nitrate changed little where sediments contain little organic material but decreased to less than 1 mg/L where sediments contain abundant organic material. Thus, riparian woodlands had little effect on the elevated concentration of nitrate in ground water that flowed beneath them; however, riparian woodlands can reduce the concentration of nitrate in ground water recharged by surface runoff that infiltrated through the riparian woodland soils. Riparian woodlands can also remove sediment and nutrients in surface runoff, as shown in other studies.

Ground-water flow was affected by the sediment grain size, the saturated thickness of the aquifer, and the presence of riparian woodland. Fine-grained sediments can reduce the saturated thickness of the surficial aquifer and disperse ground water that discharges to an estuary across a large area. Evapotranspiration through the riparian woodlands was an important pathway for ground-water discharge. The fate of nitrate in this water is uncertain: (1) Part of the nitrate can denitrify in the soils that contain abundant organic material around the roots; (2) part of the nitrate can be incorporated in the cell tissue of the trees; (3) part of the nitrate can be stored in the trees as excess nitrogen for later use; and (4) part of the nitrate can be transported to leaf surfaces. Nitrate that is transported to leaf surfaces can be transported to the atmosphere by evaporating water, or remain as salt residue on the leaves. This residue can wash from the leaves and be transported to the land surface by subsequent precipitation.

These relations can have important implications for planning and management of land uses. These implications can apply to land uses, contaminants, and geohydrologic and geochemical environments other than those studied. The effects observed on nitrate beneath agricultural fields would be similar to the effects on nitrate beneath residential areas and other land uses. Thus, types, amounts, and timing of fertilizer application to fields and residences, the density of septic tanks, and other land-use and management practices can affect the loading of nitrate to the ground water. Once nitrate is in the ground water, naturally occurring geochemical processes can reduce the nitrate concentration and loads in ground water discharging to an estuary; locating land uses that are sources of nitrate where geochemical processes reduce nitrate concentrations and loads will increase the protection of the estuaries. Additionally, the transport of contaminants through the ground water can be affected by human alterations to the ground-water-flow system in an area. Ditches in a wetland can provide a "short-circuit" pathway by which discharging ground water will runoff into an estuary, and cutting trees in, and near, a wetland can reduce the rate of evapotranspiration and increase the rate at which discharging ground water having elevated concentrations of nitrate or other contaminants will runoff into an estuary. Therefore, the types of land use and how the land is managed in a particular geohydrologic and geochemical environment can affect the transport, retention, or geochemical alteration of contaminants and how the contaminants are transported through, and are discharged from, the surficial aquifer to coastal waters.

INTRODUCTION

The Eastern Shore of Virginia forms the southern tip of the Delmarva Peninsula and separates the lower Chesapeake Bay from the Atlantic Ocean (fig. 1). The Eastern Shore consists of a central upland flanked by freshwater wetlands, saltwater marshes, tidal creeks, bays, inlets, and barrier islands. Uplands are heavily agricultural areas that, in combination with limited residential development, have a widespread effect on the water quality of the surficial aquifer (Hamilton and Shedlock, 1992; Hamilton and others, 1993). Elevated nitrate concentrations are the most common effect of land use on ground-water quality that is of concern to planners and managers in the area, because nitrate can contribute to eutrophication and can adversely affect drinking-water supplies. Ground-water nitrate concentrations exceeding the maximum contaminant level, or MCL, of 10 mg/L as nitrogen (N) (U.S. Environmental Protection Agency, 1995) have been identified on the Eastern Shore (Hamilton and Shedlock, 1992; Hamilton and others, 1993).

Planners, managers, and the agricultural community on the Eastern Shore are attempting to develop management plans and practices that will control the concentration of nitrate in ground water that discharges to Chesapeake Bay, its tributary estuaries, and estuaries on the Atlantic Ocean side (seaside) of the Eastern Shore. Knowledge of the processes that affect the concentration of nitrate in ground-water discharge, the environments in which these processes take place, and the locations of these environments will help in the development of effective nutrient-management plans that minimize cost by incorporating the effects of riparian areas, aquifer sediments, and other parts of the natural system without unduly emphasizing the effects of any one part of the system. Thus, in 1991, the U.S. Geological Survey (USGS), in cooperation with Accomack and Northampton Counties (through the Accomack-Northampton Planning District Commission and the Eastern Shore of Virginia Ground Water Study Committee), began a study of the effects of processes in different geohydrologic and geochemical environments on the concentration of nitrate in ground water in, and near, selected areas of ground-water discharge.

Nitrogen and phosphorus are essential nutrients for the growth of algae in aquatic systems. Although phosphorus usually limits growth of algae in fresh-water systems, nitrogen frequently limits growth of algae in estuaries (Stumm and Morgan, 1981). Consequently, an elevated concentration of nitrogen can stimulate algal growth and can contribute to the eutrophication of estuaries.

Nitrogen is present in aquatic systems in several species, including nitrogen gas, organic nitrogen, ammonium ion, nitrite ion, and nitrate ion. Inorganic species of nitrogen are used by algae to synthesize essential organic compounds, the mechanism by which nitrogen contributes to eutrophication. Although nitrogen gas can be fixed into organic nitrogen by certain blue green algae, the role of nitrogen gas in the eutrophication of coastal waters is limited. Nitrite ion does not significantly contribute to eutrophication because nitrite ion is not stable in oxygen-rich water and, therefore, is usually present in low concentration. Consequently, ammonium ion and nitrate ion are the primary nitrogen species that serve as nutrients and contribute to eutrophication. Nitrate ion commonly is present in greater concentration than ammonium ion in ground water because of the nitrification of ammonium ion (the microbially mediated chemical oxidation of ammonium ion) to nitrate ion, or because of the immobilization of ammonium ion by cation exchange on silt and clay in soils, aquifers, and confining units through which water flows. Consequently, an elevated concentration of nitrate in ground water that discharges to an estuary can contribute to the eutrophication of the estuary.

Although dissolved species of nitrogen that serve as nutrients are naturally present in aquatic systems, concentrations tend to be low; human activities, however, can significantly increase these concentrations. Common human activities that are sources of nitrogen species in shallow ground water include agricultural and residential application of fertilizers to the land surface, disposal of human and animal wastes, and discharge of septic-tank effluent to the ground water.

Nitrogen transformation processes are controlled by the availability of dissolved oxygen in ground water. Organic nitrogen can mineralize to ammonium whether or not dissolved oxygen is present. In the presence of sufficient dissolved oxygen, ammonium nitrifies to nitrate. When low concentrations of dissolved oxygen (concentration near 0 mg/L) inhibit nitrification, ammonium generally remains as ammonium, and nitrate can undergo denitrification (the microbially mediated chemical reduction of nitrate) to form nitrogen gas (the most common

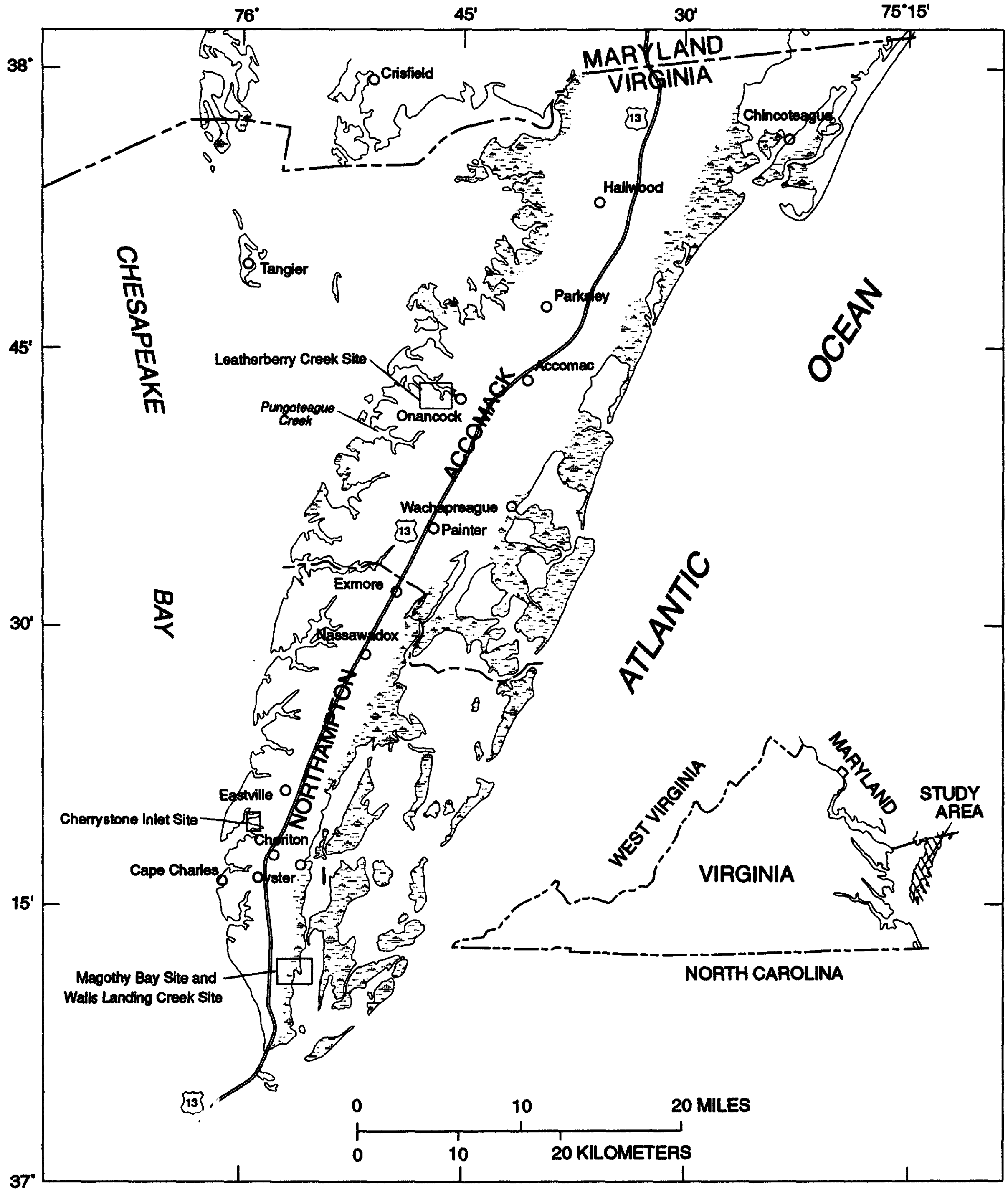


Figure 1. Location of the Eastern Shore, Virginia, and local study areas.

product) or ammonium. The mineral composition and organic content of sediments is the principal sediment characteristic that affect the ground-water chemistry.

Directions and rates of ground-water flow also affect the transport of nitrogen species from their sources toward areas of discharge to surface waters. In sedimentary ground-water systems, sediment grain size and the interspersion and interlayering of sediment of different grain size are the principal sediment characteristics that affect aquifer and confining unit permeability and ground-water flow. Topography also affects ground-water flow; ground water generally flows from uplands to lowlands where it discharges to wetlands and surface waters.

In sedimentary ground-water systems, sediment characteristics that affect ground-water flow and chemistry result from a combination of factors, including the grain size of sediment available for deposition, the type and amount of organic material available for deposition, the mineral composition of sediment available for deposition, the environments in which the sediment was deposited, and the geochemical changes in the sediment that occur after deposition (Selley, 1978). These sediment characteristics are controlled by the local topography, hydrology, and sea level at the time of deposition. The current topography in the form of scarps, terraces, flood plains, and other features results from a combination of sediment deposition and subsequent erosion and, therefore, can reflect spatial variability in underlying sediment characteristics. Furthermore, these topographic features often control current land use and cover, partly through their effect on the ground-water flow in an area. Thus, the presence or absence of agricultural fields, woodlands, and wetlands, in conjunction with the topography, can reflect underlying patterns in sediment characteristics and the associated ground-water flow and chemistry.

Riparian buffers of vegetation (commonly consisting of grass-covered areas, shrub-covered areas, marshes, or woodlands) are present in lowland wetlands along many nontidal creeks, tidal creeks, and estuaries, on slopes between uplands and wetlands, and on slopes between uplands and water bodies. Vegetated riparian areas can improve the quality of surface runoff and are thought to improve ground-water quality (Gilliam, 1994). Much of the effect that riparian areas have on ground-water quality, however, is likely to be in the shallow part of the surficial aquifer in water that recharges, or discharges, through the riparian soils and not on ground water that was recharged in the uplands and flows beneath the riparian area. Recharge through riparian areas generally will consist of precipitation that falls directly on the area and surface runoff from upland fields. Precipitation that falls directly on riparian areas has a naturally low concentration of nitrate and other constituents. Surface runoff from upland fields can have an elevated concentration of nitrate and other constituents as a result of agricultural practices. Surface runoff from upland fields that infiltrates through the soil of the riparian area can evaporate and leave a salt residue in the soil. Precipitation and surface runoff from the upland fields can dissolve the salt residues that remain in the soil of the riparian areas. Nitrate in the surface runoff can denitrify when the runoff percolates through shallow (in, and near, the root zone), riparian soils that contain abundant organic material and recharges the ground water. The concentration of nitrate in ground water that is recharged through uplands and flows beneath riparian areas probably will change little unless the concentration of dissolved oxygen becomes sufficiently low because of contact time in the aquifer or because the composition of the sediments through which the ground water flows differs beneath the riparian area from that beneath the uplands. Differences in the composition of deep sediments (below the root zone) result less from the effects of current riparian vegetation than from the effects of depositional environments. Thus, where sediments contain greater amounts of organic material as a result of the depositional environment, depletion of dissolved oxygen and denitrification are enhanced.

Depositional environment also affects ground-water flow because of its effects on sediment permeability and topography. Generally, where sediments are fine grained, the permeability of the sediments tends to be low. Low permeability inhibits ground-water flow and can contribute to the discharge of ground water. Fine-grained sediments frequently underlie flat lowlands because these flat areas reflect low-energy environments that deposit fine-grained sediments. Topography also contributes to ground-water discharge because ground water commonly discharges at the base of scarps and to flat lowlands. Such discharge frequently provides the conditions that support wetlands. Consequently, depositional environment can be a major reason that riparian wetlands are present in the flat lowlands. Additionally, fine-grained sediments often contain more organic material than coarse-grained sediments; therefore, fine-grained sediments that contain abundant organic material commonly underlie lowlands that contain riparian woodlands.

Evapotranspiration by riparian vegetation can also affect ground-water flow. Evapotranspiration can remove large quantities of ground water directly from the saturated zone or indirectly by inducing upward flow of water from the water table through the unsaturated zone to the plant roots. Thus, riparian vegetation can significantly affect the paths of ground-water flow and, thereby affect the quantity of water and associated nutrient loads discharged to estuaries and other surface-water systems. Where riparian vegetation is of limited extent and ground water almost directly discharges from upland fields to estuaries, the effects of evapotranspiration and denitrification can be limited.

Purpose and Scope

This report presents a description and comparison of the effects of different geohydrologic and geochemical processes in, and near, selected coastal ground-water-discharge areas on the concentration of nitrate in ground water discharging to coastal waters of the Eastern Shore of Virginia. The implications of these effects on the selection of land-use management practices designed to limit the concentration of nitrate in ground-water discharge also are discussed.

Four study sites were selected to represent environments in which contrasting geohydrologic and geochemical processes predominate. In these environments, ground water recharges through either fine-grained sediment or coarse-grained sediment and discharges to either an estuary, a wooded wetland and saltwater marsh, or a nontidal creek. The effects of sediment grain size (as it controls permeability), the organic content of the sediments, the thickness of sedimentary units, the topography, and the land cover on the local and regional ground-water flow and chemistry are discussed. Discussions of ground-water flow are based on the geology, topography, temporal variations in water levels, lateral and vertical head distributions, ground-water age, and distribution of chemical constituents in the water. Discussions of geochemistry are based on geology, ground-water quality, ground-water age, and ground-water flow. Water-level and water-quality data were collected at clusters of wells in transects that extend from upland recharge areas to, or near, ground-water-discharge areas. Water-level data are shown in hydrographs and in geohydrologic sections along the transects of wells. Water-quality data are shown in the geohydrologic sections and in diagrams of relative ionic composition of the water (Piper, 1944).

Although the sites that were selected for this study include agricultural fields, the results also can apply to residential and other land uses that contribute nitrate to ground water. Although the study emphasized the effects of geohydrologic and geochemical processes on nitrate in ground water, the transport and geochemical conversion of other contaminants in ground water also will be affected by these, or similar, processes and environments.

Literature Review

Numerous investigations provide insight into the geohydrology of the Eastern Shore of Virginia. Those investigations conducted on the Eastern Shore of Virginia and at the study sites that were selected for this study are of the greatest relevance. However, studies elsewhere on the Delmarva Peninsula provide additional insight.

Mixon (1985) describes the near-surface geology of the Eastern Shore of Virginia and adjacent parts of Maryland. The age, lithology, and depositional environment and history of the major formations are discussed. The formations also are associated with specific scarps and terraces. These descriptions are the basis for the regional geology described in this report. Soils have been mapped and described for Northampton County (Cobb and Smith, 1989); a report has not been completed for Accomack County.

Several studies have investigated the combined ground-water and surface-water resources of the Eastern Shore of Virginia. Cushing and others (1973) described the water resources of the entire Delmarva Peninsula. Although data from Virginia are limited, several findings are relevant because they provide interpretations and ranges in values for geohydrologic environments around the Delmarva Peninsula that would be similar to those of the Eastern Shore. For the water years (Oct. 1 through Sept. 30) 1958–67, average annual base flow of streams ranged from 3.5 to 16.5 in/yr and averaged 8.5 in/yr, although no values were estimated for streams in Virginia. The base flow of streams represents the ground-water discharge to surface water. Recharge to the surficial aquifer of the Delmarva Peninsula equals ground-water discharge as base flow plus ground-water discharge as evapotranspiration plus the change in ground-water storage. Average annual runoff ranged from 9.2 to 18.7 in/yr and averaged 15 in/yr. Annual runoff consists of ground-water discharge plus overland flow. Annual runoff at Guy Creek near Nassawadox, Va., (USGS streamflow gaging station 01484800) averaged 15.5 in/yr during water years 1964–67. The annual runoff for water years 1965–91, however, only averaged 10.5 in/yr (Prugh and others, 1992).

Rasmussen and Andreasen (1959) calculated a hydrologic budget for a 2-year period (April 1950 through March 1952) for the Beaverdam Creek Basin in the southern part of Maryland on the Delmarva Peninsula. Annual precipitation averaged 41.41 in/yr. Of the 21.31 in/yr that recharged the ground water, ground-water storage increased 0.86 in/yr, ground-water discharge to streams averaged 10.73 in/yr, and ground-water discharge through evapotranspiration averaged 9.72 in/yr. Total evapotranspiration (including that from ground water and the unsaturated zone) averaged 25.12 in/yr. Rates of evapotranspiration are probably greater in wetlands near the streams than in uplands because the water table is closer to land surface in the wetlands than in the uplands; thus, water availability will limit evapotranspiration less in the wetlands than in the uplands. Consequently, the percentage of total evapotranspiration that is from ground water is probably greater in the wetlands because the water table is shallow.

The water quality of the surficial aquifer and the relation of the water quality to land use and ground-water flow throughout the Delmarva Peninsula were evaluated by Hamilton and Shedlock (1992) and Hamilton and others (1993). The nitrate concentration was elevated as a result of domestic and agricultural land use; water quality near the water table reflected land use within 100 to 200 ft of a well. Dunkle and others (1993) evaluated recharge dates and recharge temperatures for ground water from wells throughout the Delmarva Peninsula. Ground-water age increased with depth, and recharge temperatures at the southern tip of the Delmarva Peninsula averaged 14°C. These studies included the sites for this study where precipitation infiltrates through coarse-grained sediments, recharges the surficial aquifer, then discharges to the wooded wetland and saltwater marsh and to the nontidal creek. Reilly and others (1994) used ground-water age and flow simulation to evaluate ground-water flow at Locust Grove on the northern Delmarva Peninsula. Simulated recharge rates ranged from 8.4 to 15.6 in/yr and generally agreed well with ground-water age.

Reay and others (1992; 1993) investigated nitrate in ground water and the discharge of ground water in, and around, Cherrystone Inlet. Discharge was greater where bottom sediments were coarse-grained. Discharge also affected significantly the concentration of nitrate in the estuary.

Studies of the effects of riparian woodlands on the quality of ground water have been conducted by many researchers in many locations. Decreases in nitrate concentration in the ground water commonly are attributed to denitrification and plant uptake. Such research usually emphasizes ground-water quality near the water table and processes in soils above the water table. Lowrance (1992) evaluated changes in nitrate and chloride concentrations near the water table, and the denitrification potential within 2 ft of land surface in a 180-ft wide woodland between agricultural fields and a stream in the Coastal Plain Physiographic Province of Georgia. The concentration of nitrate decreased from 13.5 mg/L at the edge of the field to 1.80 mg/L, about 30 ft into the woodland, increased to 3.09 mg/L at the base of the slope from the upland to the lowland, about 65 ft from the field, and decreased to 0.81 mg/L about 15 ft from the stream, 165 ft from the field. The concentration of chloride was 16.02, 18.87, 12.58, and 7.54 mg/L at the same sites, respectively. Denitrification potential was concentrated in the upper 4 in. of soil, which was above the water table. Lowrance (1992) concluded that plant uptake by shallow roots and the filtering capacity of the leaf litter removed nitrogen. The exact mechanism by which this took place relative to flow paths of the water, however, was not explained.

Jordan and others (1993) observed a similar decrease in concentration of nitrate beneath a riparian woodland, followed by a rise in concentrations of nitrate and chloride near the base of the slope adjacent to a flood plain and a decrease in concentrations of nitrate and chloride toward a stream in Maryland. The area at the base of the slope was an area where velocities of surface runoff from the fields eroded surficial sediments. Changes in concentration of nitrate were attributed to denitrification; possible effects of recharge by agricultural runoff were not considered.

Description of Study Area

The Eastern Shore of Virginia forms the southern tip of the Delmarva Peninsula and separates Chesapeake Bay to the west from the Atlantic Ocean to the east (fig. 1). The Eastern Shore is approximately 70 mi long and narrows from about 15 mi wide in the north to less than 1 mi wide in the south. The Eastern Shore consists of a central upland that forms a gently rolling ridge flanked by scarps and lowland terraces toward Chesapeake Bay and the Atlantic Ocean. Major scarps and terraces are associated closely with different geologic formations that have varied sediment characteristics (Mixon, 1985). Although the major scarps and terraces have been identified and mapped, small ones have not been mapped. Land-surface altitude generally ranges from 30 to 50 ft above sea level in the uplands and decreases to sea level across the scarps and terraces. Topographic relief generally is low relative to that in many other parts of the country; land-surface declines are less than 10 ft across more than 100 ft across many scarps, where relief is the greatest. Because the Eastern Shore is narrow, the only surface drainage consists of short nontidal creeks that flow east or west from the center of the peninsula to tidal creeks, bays, and inlets discharging into Chesapeake Bay and the Atlantic Ocean. Precipitation readily recharges the ground-water system because surficial sediments generally are permeable; thus, ground water is the major source of fresh water.

On the western side of the southern tip of the Eastern Shore, terraces are absent and bluffs up to 60 ft above sea level border Chesapeake Bay. No nontidal creeks drain from the uplands to the bay in this area. A short distance north, terraces lie between the uplands and Chesapeake Bay. The terraces are dissected by tidal creeks and inlets that form peninsulas locally known as necks. Nontidal creeks that drain the uplands flow into the tidal creeks and inlets. These terraces widen to the north and gently slope toward Chesapeake Bay. About half way up the Eastern Shore, near the Accomack/Northampton County line, saltwater marshes border Chesapeake Bay on the lowest parts of the terraces. These marshes are dissected by tidal creeks and generally widen to the north.

A series of saltwater marshes, tidal creeks, bays, inlets, and barrier islands lie on the lowest terraces that form the eastern side of the Eastern Shore. These protect the mainland from the full force of storms over the Atlantic Ocean. The most seaward barrier islands are from 1 to 10 mi from the mainland. Nontidal creeks that drain to the east flow into the tidal creeks and bays. The altitude of land surface adjacent to the saltwater marshes, tidal creeks, and bays tends to be greater in the north than in the south.

Geology

Mixon (1985) provides the basis for the following description of the regional geology. Near-surface sediments beneath the central upland of the Eastern Shore are of Pleistocene age or younger and are underlain by sediments of the Yorktown Formation and deeper formations of Tertiary age and older. The near-surface sediments were deposited as two barrier-spit or barrier-island complexes in a combination of low-energy marsh and estuarine environments; high-energy, shallow-water environments near the shore; and low-energy, deeper-water environments farther from the shore. Fine-grained sediments were deposited in the low-energy environments; coarse-grained sediments were deposited in the high-energy environments. Sediments of the northern complex form the Accomack Member of the Omar Formation of Pleistocene age (figs. 2 and 3). Sediments of the southern complex form the Pleistocene Nassawadox Formation with the Butlers Bluff Member to the east and the Occohannock Member to the west. The Stumptown Member underlies parts of the Butlers Bluff Member and the Occohannock Member, but because the Stumptown Member is relatively deep and has little effect on geohydrology and geochemistry of the surficial aquifer, it is not discussed in this report.

Parts of the originally deposited sediments were eroded and were redeposited with other sediments to form a series of Pleistocene terraces during subsequent lower stands of the sea. These terraces were deposited in a variety of high-energy and low-energy environments similar to those in which the original sediments were deposited. Environments on the bay side of the upland tended to have lower energy than environments on the seaside because the peninsula reduced the wave energy.

Two Pleistocene terrace deposits border the eastern side of the uplands. Deposits that lie beneath the uppermost terrace form the Joynes Neck Sand.

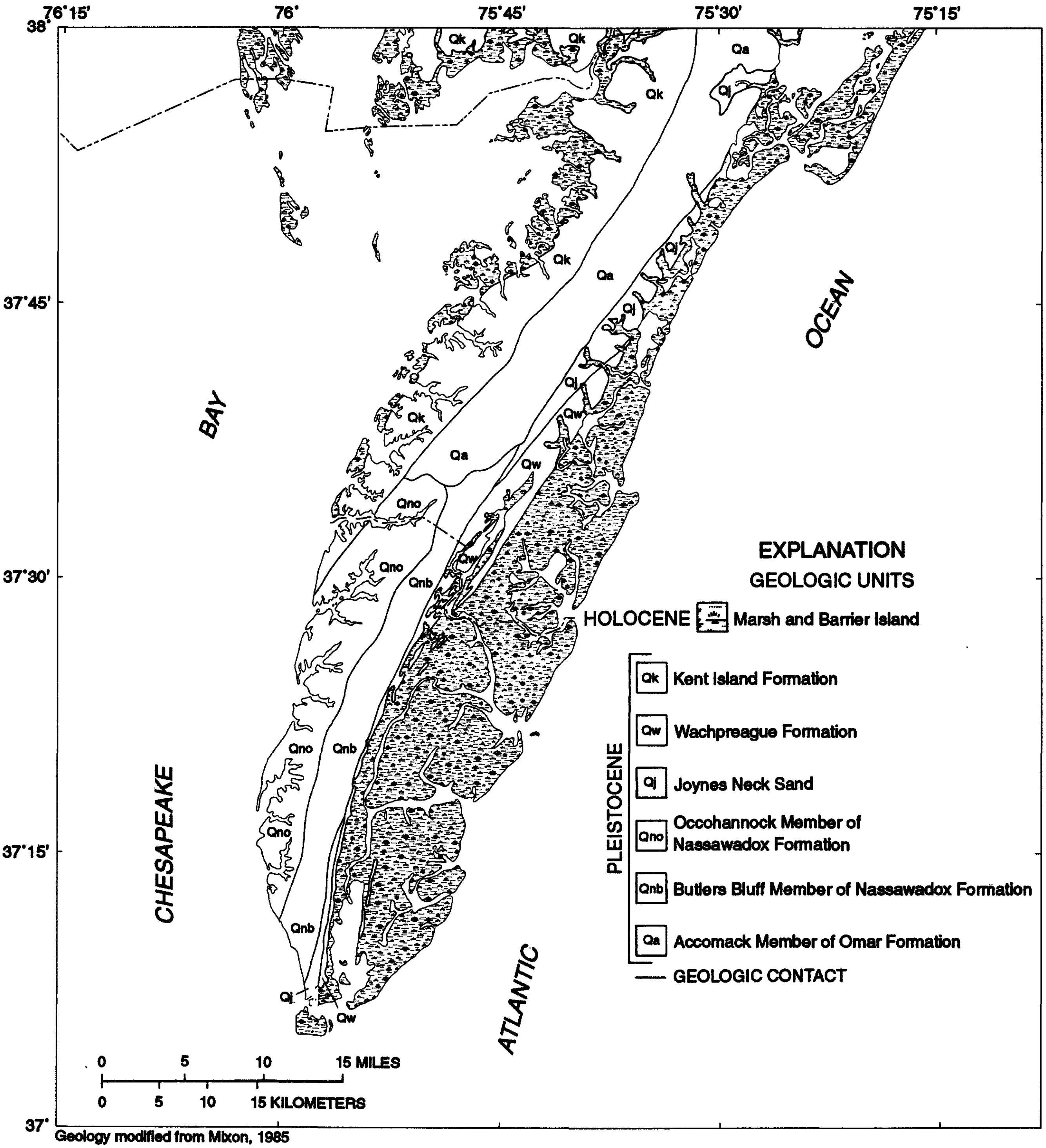


Figure 2. Shallow geology of the Eastern Shore, Virginia.

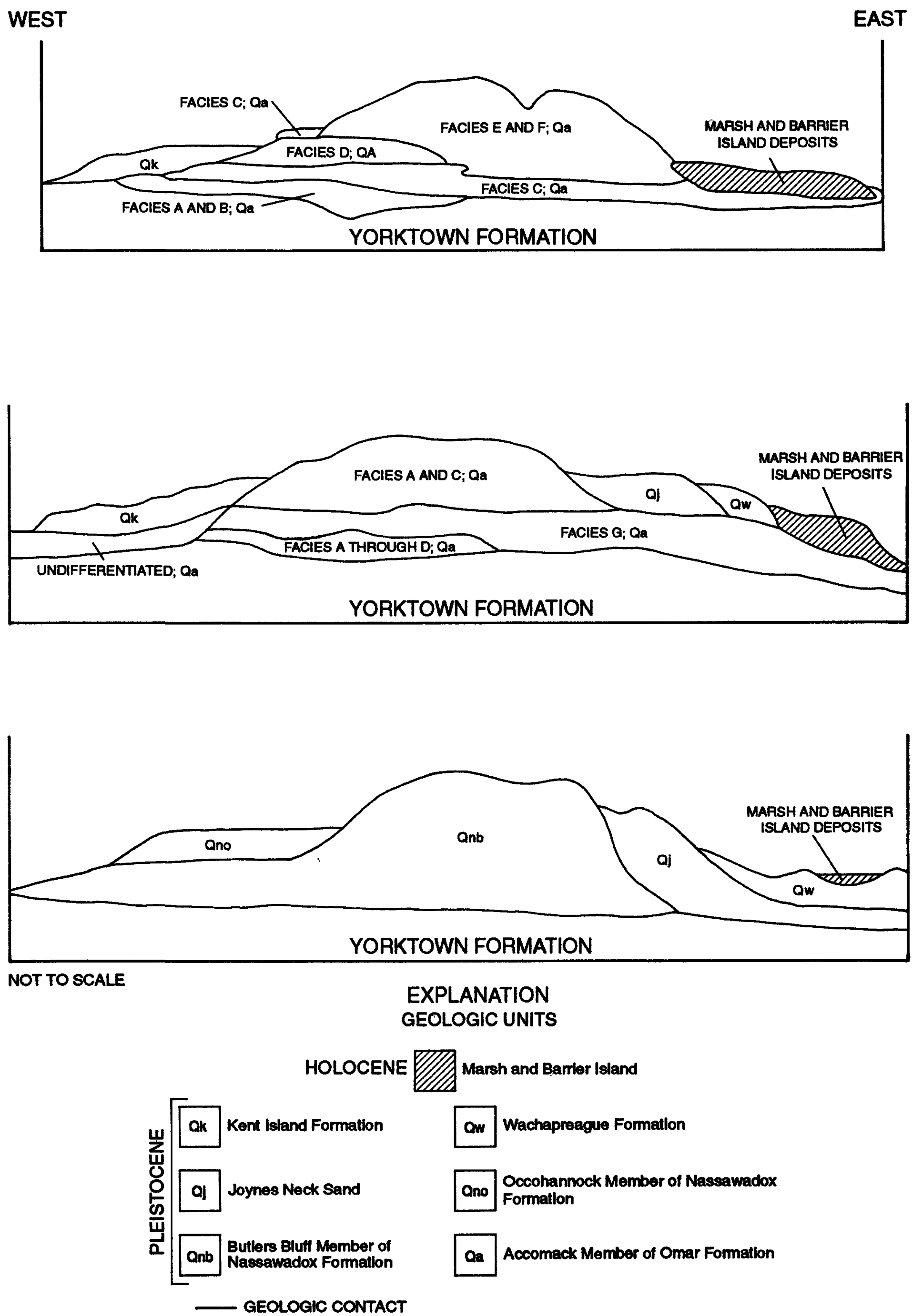


Figure 3. Generalized geologic section across the northern, middle, and southern Eastern Shore, Virginia.

This terrace lies from 15 to 25 ft above sea level. The Joynes Neck Sand is geographically split into two parts: (1) a northern part borders much of the Accomack Member of the Omar Formation; (2) a southern part borders the southern quarter of the Butlers Bluff Member of the Nassawadox Formation. Deposits beneath the lower terrace form the Wachapreague Formation. The Wachapreague Formation borders most of the remainder of the Butlers Bluff Member of the Nassawadox Formation, about half of the northern part of the Joynes Neck Sand, and most of the southern part of the Joynes Neck Sand.

The Kent Island Formation forms the terrace on the western flank of the entire Accomack Member of the Omar Formation and the northern part of the Occohannock Member of the Nassawadox Formation (figs. 2 and 3). The Kent Island Formation lies west of one of two scarps and is generally less than 25 ft above sea level. The Kent Island Formation is bordered to the west by Holocene marsh deposits and Chesapeake Bay and its tributaries. The remainder of the western edges of both members of the Nassawadox Formation directly borders Chesapeake Bay.

The Accomack Member of the Omar Formation is a sequence of gravel, sand, silt, clay, and peat that probably was deposited during a single transgression, or rise, of the sea. These sediments are as much as 80 ft thick and thin from the center of the peninsula toward the east and west where they are truncated and overlapped by the younger Joynes Neck Sand and Kent Island Formation. The Accomack Member of the Omar Formation consists of seven lithic facies identified by Mixon (1985) as facies A through G. These facies represent a seaward progression in depositional environments. A thin basal gravelly sand (facies A) is overlain by two facies (facies B and C) that generally consist of peat and (or) organic rich mud, silt, clay, sand, and shell. Typically the sediments are fine-grained with sands generally muddy, silty, and clayey. Wood and other organic material are abundant in the sediments. These sediments were deposited in low energy environments ranging from landward parts of saltwater marshes to lagoons. The overlying facies (facies D) consists of bedded fine-grained to coarse-grained muddy sand that appears to have been deposited in higher energy parts of the barrier-island system than the underlying facies, probably open lagoon and barrier-inlet environments. These sediments probably contain abundant organic material as indicated by their medium to dark gray color. A gravelly sand facies (facies E) appears to result from the reworking of sediments by waves and currents in a high-energy marginal marine environment. The laminated, gently dipping bedded sands of facies F indicate deposition in beach and nearshore environments. Facies E and F appear to have little organic material. Fine-grained muddy sands of facies G were deposited seaward of facies E and F along the shallow nearshore shelf.

Although sediments of the Accomack Member are part of a single transgressive depositional sequence, not all facies are presents at all locations. Mixon (1985) indicates a general sequence in sediment characteristics from north to south and east to west. In northern Accomack County a wedge that consists of the fine-grained, sediments that contain abundant organic material of facies B, C, and D increases in thickness to the west and is overlain by a wedge of coarse-grained sediments of facies E and F that increases in thickness to the east. To the south, a thin deposit of facies A through D underlies the western part of the upland, facies G underlies most of the uplands, and deposits of facies E and F that are fairly uniform in thickness overlie facies G. Although facies G was deposited in environments farther from shore than facies E and F, it was overlain by sediments of facies E and F where the Accomack barrier spit was deposited progressively farther to the south over previously deposited sediments of facies G. Thus, a wedge of fine-grained, sediments that contain abundant organic material lies at, or near, the surface in northwestern Accomack County and decreases in thickness to the east and south. These sediments are overlain by coarse-grained sediments that contain little organic material and increase in thickness to the east and south.

The Butlers Bluff and Occohannock Members of the Nassawadox Formation contain relatively coarse-grained sediments that contain little organic material. These sediments appear to have been deposited in a near-shore environment. The Butlers Bluff Member is as much as 60 ft thick and generally consists of clean, pale gray to light yellowish-gray, fine-grained to coarse-grained gravelly sand. The Butlers Bluff Member consists of two interlayered sediment types: (1) a poorly sorted medium-grained to very coarse-grained pebbly sand that predominates in the upper part of the member; (2) a relatively well sorted, fine-grained to medium-grained sand that predominates in the middle and lower parts of the member. The Occohannock Member overlies the Butlers Bluff Member to the west and consists of light yellowish-gray, fine-grained to medium-grained sand that commonly is 7 to 20 ft thick. A local basal pebbly sand, 4 to 12 in. thick, is overlain by a fine-grained to medium-grained sand that forms the lower and middle part of the unit. The uppermost 5 ft that forms the soil zone consists of a gravelly loam. On the basis of sediment size and horizontal bedding, the Occohannock Member appears to have been deposited in a lower-energy environment than the Butlers Bluff Member.

The Joynes Neck Sand consists of loose, fine-grained to coarse-grained, yellowish-gray quartz sand, in part interbedded with pebbly sand and sandy gravel (Mixon, 1985). The Joynes Neck Sand is an upward fining sequence that probably was deposited in a near-shore environment during a single marine transgression when the Butlers Bluff Member of the Nassawadox Formation was deposited. The lower part consists of medium-grained to coarse-grained sand and abundant pebbles, and the upper part consists of fine-grained to medium-grained, well-sorted quartz sand that contains abundant heavy minerals.

The Wachapreague Formation extends seaward of the lowest major scarp and underlies Holocene coastal marsh and lagoon systems. In a borehole near Wachapreague that is designated as the type section, the Wachapreague Formation consists of two lithic units: (1) a lower, 20-ft-thick unit of clayey and silty, fine-grained to very fine-grained gray sand and clay-silt; (2) an upper yellowish-gray, medium-grained to coarse-grained gravelly sand (Mixon, 1985). The contact between these units is about 10 ft below sea level. The Wachapreague Formation is exposed at the land surface in marshes as raised hummocks that have a north to northeast linear orientation. This exposure results from deposition in a combination of beach ridges, cuspate spits, and lagoons. A system of sandy barrier islands forms the eastern limit of the present-day exposed land surface.

The Kent Island Formation underlies the lowland that gently slopes toward Chesapeake Bay and extends 125 mi north from near the Accomack/Northampton County line through Maryland to the northern end of the Bay. The thickness of the Kent Island Formation ranges from 3 to 20 ft. In Virginia, the sediments of the Kent Island Formation differ from north to south with the change taking place in the vicinity of Onancock. In the north, sediments are similar to those of the Accomack Member of the Omar Formation. The basal part of the unit consists of a coarse-grained to very coarse-grained gravelly sand with the middle and upper parts consisting of poorly sorted, clayey and silty, fine-grained to medium-grained, gray sand that locally includes peat up to 2 ft thick. In the south, the upper part of the formation consists of moderately well sorted to well sorted, fine-grained to medium-grained, yellowish-gray sand that is generally finer grained than the sediments to the north. These sediments grade downward into either a gray to grayish-orange, medium-grained to coarse-grained pebbly sand or a clayey and silty shelly sand. Thus, the Kent Island Formation consists of fine-grained, sediments in its upper parts, but locally may contain coarse-grained sediments that contain little organic material, particularly in its lower parts and to the south.

For the purpose of this report, these formations can be grouped into two major categories: (1) formations that primarily consist of medium-grained to coarse-grained sand and gravel and contain little organic material (referred to as coarse-grained in this report); (2) formations that primarily consist of fine-grained to medium-grained sand, silt, and clay that typically contain abundant organic material (referred to as fine-grained in this report). Generally, facies E and F of the Accomack Member of the Omar Formation, the Butlers Bluff and Occohannock Members of the Nassawadox Formation, and the Joynes Neck Sand can be classified as coarse-grained. Facies B, C, D, and G of the Accomack Member of the Omar Formation and the Kent Island Formation can be classified as fine-grained. The Wachapreague Formation consists of both coarse-grained and fine-grained sediments.

Hydrology

The Eastern Shore has little fresh surface water; water users primarily depend on ground water for supplies of fresh water because ground water is abundant and streams are small. Agricultural irrigation is the principal use for fresh surface water. Surface water is withdrawn from small ponds created by dams on the nontidal creeks and by excavating pits in the shallow sediments. Water is primarily supplied to the excavated ponds by the shallow ground-water system. Ground water also supplies water to creeks, and the ponds created on them, during base-flow periods.

Thus, ground water is an important resource on the Eastern Shore.

Precipitation that falls on the Eastern Shore either recharges the ground-water system or is discharged as surface runoff or evapotranspiration. Annual precipitation at the weather station near Painter averages 42.44 in/yr (National Oceanic and Atmospheric Administration, 1992).

Local recharge provides the only freshwater to the ground-water system. The ground-water system consists of an upper surficial aquifer that generally reflects unconfined, or water-table, conditions, underlying confined aquifers, and intervening confining units. Confining units inhibit, but do not prevent, the flow of water between aquifers. The only freshwater aquifers are the surficial aquifer and the upper, middle, and lower Yorktown-Eastover aquifers (Richardson, 1994). Salty ground water is present throughout all aquifers that lie beneath the Yorktown-Eastover aquifers and it is present in most parts of the surficial and Yorktown-Eastover aquifers that lie beneath Chesapeake Bay and the Atlantic Ocean. Depending on conditions, salty ground water can be present locally in parts of these aquifers beneath the peninsula.

The surficial aquifer consists of permeable sands and gravels of the near-surface formations and locally can include sands and gravels of the upper part of the Yorktown Formation that overlie the uppermost confining unit. The uppermost confining unit consists of fine-grained sand, silt, and clay of the upper part of the Yorktown Formation and locally can include fine-grained sand, silt, and clay in the lower parts of the near-surface formations. Paleochannels of permeable sand and gravel are present within the confining unit.

Precipitation recharges the surficial aquifer throughout most of the Eastern Shore. The annual recharge rate to the surficial aquifer probably differs spatially. At Beaverdam Creek on the Delmarva Peninsula in the southern part of Maryland, ground-water recharge averaged 21.31 in/yr with 10.73 in/yr of the ground water discharged to streams, 9.72 in/yr of the ground water discharged through evapotranspiration, and 0.86 in/yr increase in ground-water storage from April 1950 through March 1952 (Rasmussen and Andreasen, 1959). Cushing and others (1973) found that ground-water discharge to base flow of streams ranged from 3.5 to 16.5 in/yr and averaged 8.5 in/yr throughout the Delmarva Peninsula from October 1958 through September 1967. In the

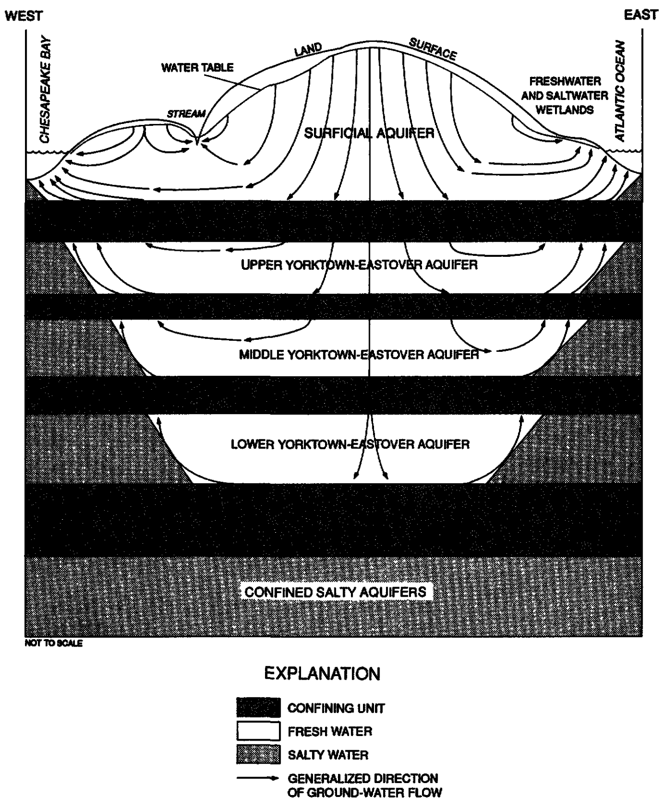


Figure 4. Generalized ground-water flow beneath the Eastern Shore, Virginia. (Modified from Richardson, 1994, figure 10.)

Beaverdam Creek Basin, ground-water discharge averaged 11.8 in/yr for that same period. The range in ground-water discharge through evapotranspiration at a given location is uncertain but probably varies with vegetation and depth to the water table. In wetlands, rates of ground-water discharge through evapotranspiration are high because of the dense vegetation and shallow water table.

Recharged water flows vertically and laterally through the surficial and confined aquifers until it discharges to ponds, nontidal and tidal creeks, wetlands (including wooded wetlands and saltwater marshes), estuaries, or wells. Ground water tends to discharge to areas of low topography, except for the wells and some ponds. Some areas can function seasonally as either recharge or discharge areas depending on geohydrologic conditions.

Depending on the location, freshwater recharge to the surficial aquifer can either flow vertically into the underlying confined aquifers or remain in the surficial aquifer (fig. 4). Generally, water that recharges near the center of the peninsula flows deeper and remains in the aquifers longer than water that recharges closer to the shores of the peninsula. Water that recharges near the center of the peninsula flows downward from the surficial aquifer through the confining units to recharge the confined aquifers; water that recharges to the east and west of this central recharge area remains in the surficial aquifer. Recharge to the confined aquifers averages 0.6 in/yr (Richardson, 1994). Recharge from the surficial aquifer to the confined aquifers is a small percentage (probably less than 10 percent) of the total recharge to the surficial aquifer because of the low permeability of the confining units.

Water in the confined aquifers flows laterally from the center of the peninsula toward the coast where it discharges to the surficial aquifer or directly to surface waters. Unless surface-water bodies fully incise through the surficial aquifer, water that discharges from the confined aquifers again must flow through the surficial aquifer before discharging to the surface. Water in the surficial aquifer flows laterally to ponds, nontidal and tidal creeks, wetlands, and estuaries where it discharges. Ground water that discharges to areas that are farther from the recharge area is older and has flowed along a longer and deeper ground-water-flow path than ground water that discharges closer to the recharge area (fig. 4). Thus, water that remains in the shallow part of the surficial aquifer discharges sooner and closer to the recharge area than water that flows through the confined aquifers. In some discharge areas, only ground water from shallow parts of the system discharges. In other areas, water from shallow and deep parts of the ground-water system discharges.

The geohydrologic conditions in discharge areas can affect the amount of ground water that flows toward the estuaries on the Chesapeake Bay side and seaside of the peninsula. All nontidal creeks on the Eastern Shore discharge into tidal creeks and estuaries that border the peninsula. Base flow of nontidal creeks is provided by ground-water discharge. Ground water also discharges directly to the estuaries and to wetlands. The amount of ground-water discharge and the location of discharge areas are affected by several factors that include the grain size of the sediments through which the water flows, the topography, and the overlying land cover. The grain size of the sediments is important because the coarse-grained, permeable sediments allow ground water to flow and discharge more readily than fine-grained sediments that have low permeability.

Topography, in part, controls the saturated thickness of the surficial aquifer and the hydraulic gradient (slope in the water table) that establishes the direction and rate of ground-water flow to creeks, wetlands, and estuaries. The altitude of the water table beneath the uplands is usually considerably greater than that of the creeks, wetlands, and estuaries. Consequently, the altitude of the water table declines as ground water flows from uplands toward the creeks, wetlands, and estuaries. As the altitude of the water table declines beneath the uplands, the saturated thickness of the surficial aquifer decreases; the hydraulic gradient and the rate of ground-water flow increase laterally because the same amount of water (or even more because of additional recharge) must flow through a smaller saturated thickness. Hydraulic gradients decrease beneath the lowlands because of the low topographic gradient and the altitude of the creeks and estuaries to which the ground water discharges is near that of the wetlands. Consequently, because the reduced saturated thickness and low hydraulic gradient allow less ground water to flow through the aquifer beneath the lowlands than beneath the uplands, ground water flows sluggishly and discharges to the land surface to form wetlands. Vegetation in, and near, wetlands and other discharge areas can intercept shallow ground water and discharge it to the atmosphere through transpiration. This water and the dissolved constituents it contains may no longer be available for discharge to the creeks or estuaries. Water at, or near, land surface can evaporate directly to the atmosphere.

Land Use

The Eastern Shore is not intensively developed; marshes, wetlands, and tidal areas cover 53.2 percent of the area, and agriculture and woodlands cover 38.3 percent of the area. More intensive land uses include residential (3.2 percent of the area), recreational (1.6 percent), institutional (0.8 percent), industrial (0.5 percent), commercial (0.1 percent), and other (2.3 percent) uses. Much of the more intensive development is located along highway U.S. 13 and in small towns that are scattered around the peninsula. U.S. 13 is the main highway located along the center of the peninsula and is the major development corridor.

Geology, soils, hydrology, and the ability to drain the land controls much of the land use. The marshes, tidal areas, and many of the wetlands are located in the low, poorly drained, and (or) tidally inundated areas along Chesapeake Bay and the Atlantic Ocean. Wetlands also are located in poorly drained lowlands along creeks and in isolated upland areas.

In the center of the peninsula, creek valleys and slopes are wooded because the water table generally is near land surface and steep slopes make farming difficult and increase erosion potential. Uplands tend to be a mixture of agriculture and woodlands that, in part, reflect the geology, soil type, and hydrology of the area. In northern Accomack County woodlands are interspersed with small fields that have closely spaced ditches. This area is underlain by the fine-grained sediments of the Accomack Member of the Omar Formation. In the south, in Northampton County, fields generally are larger than those in northern Accomack County and have few ditches to drain them. This area is underlain by the permeable, medium-grained to coarse-grained sediments of the Nassawadox Formation and the Joynes Neck Sand. The size and interspersion of fields and woodlands tends to be controlled, in part, by how well the soils drain, based on a comparison of the soils and land cover shown on soils maps.

This relation of land use to surface drainage differs in two areas: (1) along the eastern side of the northern part of the peninsula, fields are adjacent to the water bodies because soils are well drained and land-surface altitude is high adjacent to the tidal creeks and estuaries; (2) along the western terraces that are underlain by the Kent Island Formation, land use appears to be locally controlled by the ability of water to drain from the land through surface-water and ground-water pathways to Chesapeake Bay and the tidal creeks that form the wide peninsulas. The lowlands along Chesapeake Bay are poorly drained because of the low land-surface altitude and the little relief in land surface. These areas generally have little development and are covered by saltwater marshes, freshwater wetlands, and woodlands. The centers of the peninsulas also appear to be poorly drained as indicated by the lack of developed natural surface drainage and the seasonal high ground-water levels that can reach land surface. Ground-water levels at the centers of the peninsulas probably are high, in part, because the fine-grained sediments of the Kent Island Formation, and slow drainage from the area helps maintain a seasonally high water table. Attempts to drain these areas with ditches do not appear to have been sufficient to allow crops to be raised. The only places in the uplands away from the bay that appear to be sufficiently drained to raise crops are areas within about 0.5 mi of the tidal creeks. These areas appear to have better surface-water drainage and deeper ground-water levels. Ground-water levels are deeper because ground-water levels decline as ground water flows from the center of the peninsulas toward the creeks, and land-surface altitude changes little from the center of the peninsulas to the steep banks of the creeks. Recently, residential development has been replacing agriculture along the shores of the creeks.

Description of Local Study Sites

Four local sites were selected to study the effects of geohydrologic and geochemical processes on water quality in specific geohydrologic and geochemical environments of the Eastern Shore (fig. 1). One study site was selected to evaluate the flow and chemistry of ground water discharging to an estuary from a relatively fine-grained, low-oxygen, ground-water system beneath agricultural fields. This site is located on Leatherberry Creek, a tidal creek on the northern Chesapeake Bay side of the peninsula. Three study sites were selected to evaluate the flow and chemistry of ground water discharging from coarse-grained, oxygen-rich ground-water systems beneath upland agricultural fields to different types of discharge environments. Ground water discharges directly from uplands to an estuary at a site on Cherrystone Inlet, an estuary off Chesapeake Bay. Ground water discharges to a sequence of wooded wetlands and saltwater marshes at a site adjacent to Magothy Bay on the Atlantic Ocean side of the peninsula. Ground water discharges beneath a riparian woodland to Walls Landing Creek, a nontidal creek adjacent to the Magothy Bay site; Walls Landing Creek flows into Magothy Bay.

Dominant processes affecting nitrogen transport were expected to differ at each site. Beneath uplands underlain by fine-grained sediments that contain abundant organic material, the transformation of ammonium to nitrate can be inhibited, ammonium can be immobilized on the sediments, and nitrate denitrifies after it forms, thereby limiting the amount of nitrogen discharged from the ground water to nearby estuaries. Sites where ground water discharges directly from uplands underlain by coarse-grained sediments to an estuary provide little opportunity for the natural geohydrologic and geochemical processes to reduce loads of nitrate that discharge to the estuary. Sites with a broad zone of wetlands provide the greatest opportunity for the natural geohydrologic and geochemical processes to reduce loads of nitrate in ground water discharging from coarse-grained sediments to an estuary. The quality of discharge to nontidal creeks will depend on the processes that occur beneath the flood plain. Although each site was selected to study the effects of particular conceptualized environments, local heterogeneities at each site added to the complexity of the site and the understanding of how different environments function geohydrologically and geochemically.

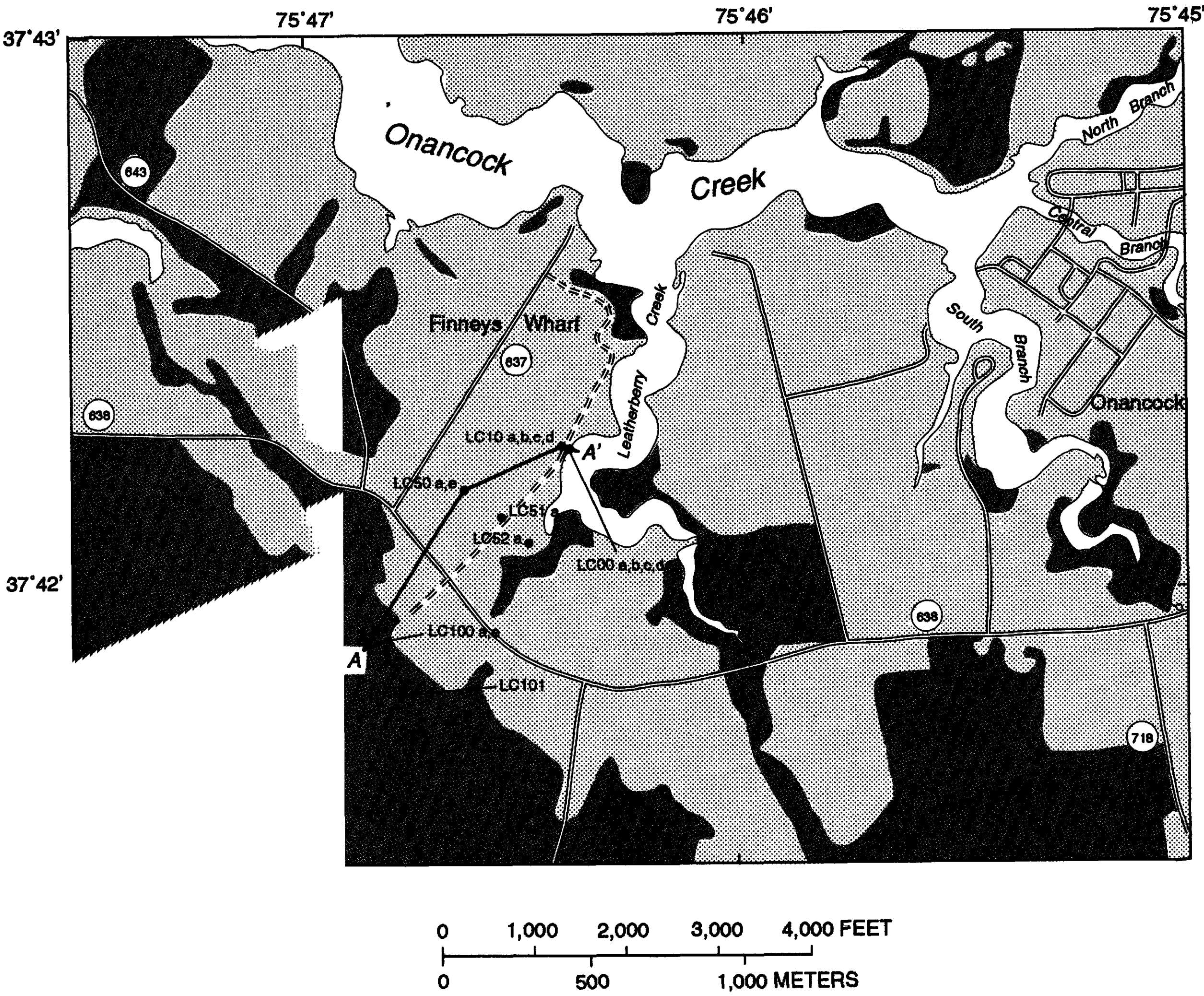
Leatherberry Creek

The site with the fine-grained upland sediments (Leatherberry Creek) is located on a 4-mi-wide peninsula bounded and drained by Pungoteague Creek to the south, Chesapeake Bay to the west, and Onancock Creek to the north (figs. 1 and 5). The site directly borders Leatherberry Creek that flows north into Onancock Creek which is one of the numerous small creeks that drain the area. Land-surface altitude gradually decreases from about 10 to 15 ft above sea level in the interior of the peninsula to the level of the bay at Chesapeake Bay; relatively steep banks as high as 15 ft border creeks away from the bay. The interior of this peninsula is primarily woodland. Agricultural fields that border the creeks generally extend less than 2,500 ft inland. Corn and soybeans were grown in alternate summers in different parts of the fields adjacent to Leatherberry Creek and wheat was grown in the winter and spring. Numerous ditches have been dug to adequately drain these fields for raising crops. Residential development is increasing along the immediate shoreline. A 100- to 150-ft-wide riparian woodland covers the approximately 10-ft-high bank between the agricultural fields and Leatherberry Creek.

The study site contains a transect of well clusters and individual wells that extend from the interior woodland across the agricultural fields and the riparian woodland to the western bank of Leatherberry Creek (Section *A–A′* (fig. 5)). The transect extends from a cluster of two wells in the interior woodlands (cluster LC100) through a cluster of two wells in the middle of the field (cluster LC50), a cluster of four wells about 20 ft from the edge of the field at the top of the bank (cluster LC10), and a cluster of four wells in the riparian woodland at the edge of Leatherberry Creek (cluster LC00). Two individual wells are located in the field between cluster LC50 and Leatherberry Creek (wells LC51a and LC52a). Although the transect does not follow a flow line, clusters represent the effects of land uses and geohydrologic and geochemical processes at different points along different flow lines that probably have similar geohydrologic and geochemical characteristics.

The site is underlain by the Kent Island Formation and is in the vicinity of the transition in sediments described by Mixon (1985). Soils maps have not been published for Accomack County where the site is located, but two distinctly different types of near-surface sediments are present at the site. Near the creek (within several hundred feet) sediments shallower than 7 ft tend to be fine-grained to medium-grained, light to medium tan sand and clayey sand. Little organic material is present, even beneath the riparian woodland. Farther inland, sediments tend to be mottled red, dark gray, and dark brown relatively fine-grained silty and clayey sand or sandy silt and clay. Organic material appears to be abundant based on the overall gray coloration of the sediments, and it appears to have been deposited with the sediments. Wells were much more difficult to drive through the sediments at this site than at all other sites, probably a result of the fine grain size of the sediments.

The sandy sediments form the surficial aquifer at this site. The altitude of the top of the underlying confining unit is uncertain but is probably about 15 ft below sea level as indicated by the regional geohydrologic framework (Richardson, 1994) and geophysical logs of wells in the area. The deepest well at the cluster at the edge of the creek (LC00d) became difficult to drive below an altitude of 10 ft below sea level and was screened from 13.9 to 16.5 ft below sea level. This well could be pumped dry after about 5 minutes of pumping at a rate of less than 1 gal/min although shallower wells at that cluster could sustain such a pumping rate. Because the permeability of sediments at the depth of LC00d is less than that of overlying sediments, these deeper sediments may be the upper part of the confining unit.



EXPLANATION

LAND USE AND COVER

Woodlands

Agriculture

A—A' LINE OF SECTION--Geohydrologic section

LC50 a,e WELL CLUSTER--Letters and numbers are identification numbers for individual wells in cluster

LC51 a SINGLE WELL--Letters and numbers are identification number

Figure 5. Locations of wells, well clusters, and other features at the site with fine-grained upland sediments adjacent to an estuary (Leatherberry Creek), Eastern Shore, Virginia.

Cherrystone Inlet

The site with upland agricultural fields underlain by coarse-grained sediments adjacent to an estuary (Cherrystone Inlet) is located on the western tip of Eyreville Neck, a peninsula formed by Old Castle Creek, Eyreville Creek, and Cherrystone Inlet (figs. 1 and 6). Land-surface altitude in the fields generally is 7 to 9 ft above sea level. Fields directly border the estuary to the south with a 7- to 8-ft bluff between the fields and the estuary. This bluff appears to result from active erosion of the shoreline by waves. Soybeans were grown in the late spring, summer, and early fall, and wheat was grown in the late fall, winter, and early spring. Natural surface drainage is poorly developed; few, if any, ditches, however, are needed to adequately drain the fields for raising crops because the soils are permeable. A riparian woodland as wide as 500 ft separates the fields from the estuary to the west and the north. Narrow saltwater marshes form part of the shoreline between the woodland and the estuary. Within the woodland, land-surface altitude gradually slopes from that of the field to that of the estuary.

A cluster of four wells was installed at the center of the field (cluster CSF50). Two transects of clusters were constructed from cluster CSF50: one through the woodland (Section *B–B'* (fig. 6)) and another to the bluff (Section *C–C'* (fig. 6)). The transect through the woodland also includes clusters of three wells at the edge of the estuary (cluster CSW00), a cluster of four wells in the woodland about 150 ft from the estuary (cluster CSW10), and a cluster of four wells between the field and woodland (cluster CSW30). The transect to the bluff contains a cluster of five wells at the edge of the bluff (cluster CSF25).

The site is underlain by the Occohannock Member of the Nassawadox Formation (Mixon, 1985). Soils at the site primarily are of the Bojac series, a very deep, well drained, fine-grained sandy loam (Cobb and Smith, 1989). Sediments beneath the fields consist of an upper reddish, fined-grained silty sand that grades to a medium-grained to coarse-grained, white to light gray sand below 6 ft. Sediments in the upper 4 ft beneath the woodland consist of light tan and gray to orange, fine-grained, silty, clayey sand and sandy clay with red and gray mottling. The clay content was sufficient in parts of these sediments to give them a plastic consistency. Below 4 ft the sediments consist of a gray, fine-grained to medium-grained silty sand. The uniformity of the gray coloration below 4 ft indicates an abundance of organic material that was deposited probably when the sediments were deposited and does not result from the current presence of the riparian woodland. Wells CSW00b, CSW10a, CSW10b, and CSW30a could be pumped dry in less than 5 minutes at a rate of less than 1 gal/min although wells of similar depth in the coarse-grained sediments (CSF25a and CSF50a) could sustain similar pumping rates. Sediments beneath the woodlands appear to be fine grained to a depth of about 12 ft and coarse grained below 12 ft, as indicated by the hydraulic response of the wells and the elevated specific conductance of the ground water (discussed in the sections "Geohydrology" and "Geochemistry" of the site). The proximity of these fine-grained sediments adjacent to Cherrystone Inlet indicate that the sediments probably were deposited in a deep water, low energy environment beneath the inlet during a previous higher stand of the sea. On the basis of topography and land cover around Cherrystone Inlet, these fine-grained sediments probably are present along the shores of the inlet, except where waves have eroded through the fine-grained sediments to expose the coarse-grained upland sediments, such as along the southern shore of the peninsula at the study site. The fine-grained sediments probably extend beneath the inlet except where the sediments were not deposited or have been eroded.

The medium-grained to coarse-grained sandy sediments at the site form the surficial aquifer. The fine-grained to medium-grained silty, clayey sand and sandy clay beneath the woodland can be characterized either as a leaky confining unit or as a part of the aquifer that has low permeability and inhibits lateral and vertical flow and discharge to the estuary. This unit will be identified as a leaky confining unit in this report because of its flow-inhibiting characteristics. The top of the confining unit that forms the base of the surficial aquifer is about 20 ft below sea level, and the top of the underlying confined aquifer is about 70 ft below sea level beneath the site (Richardson, 1994). No wells appear to be deep enough to penetrate the confining unit based on the ability of the deepest well in each cluster to sustain continuous pumping.

Magothy Bay

The site where ground water discharges from coarse-grained upland sediments to a wooded wetland and saltwater marsh (Magothy Bay) is located adjacent to Magothy Bay on the Atlantic Ocean side of

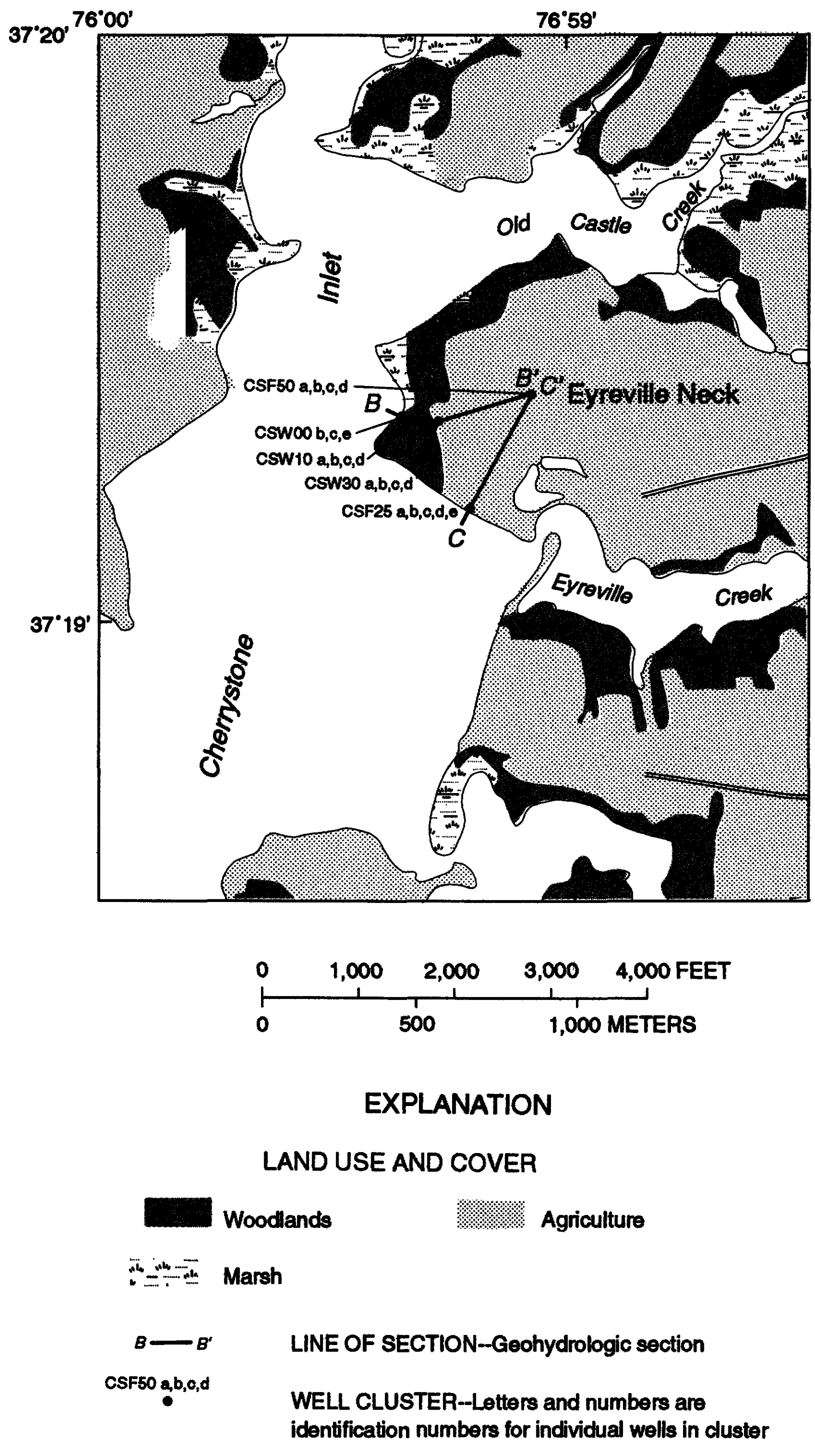


Figure 6. Locations of well clusters and other features at the site with coarse-grained upland sediments adjacent to an estuary (Cherrystone Inlet), Eastern Shore, Virginia.

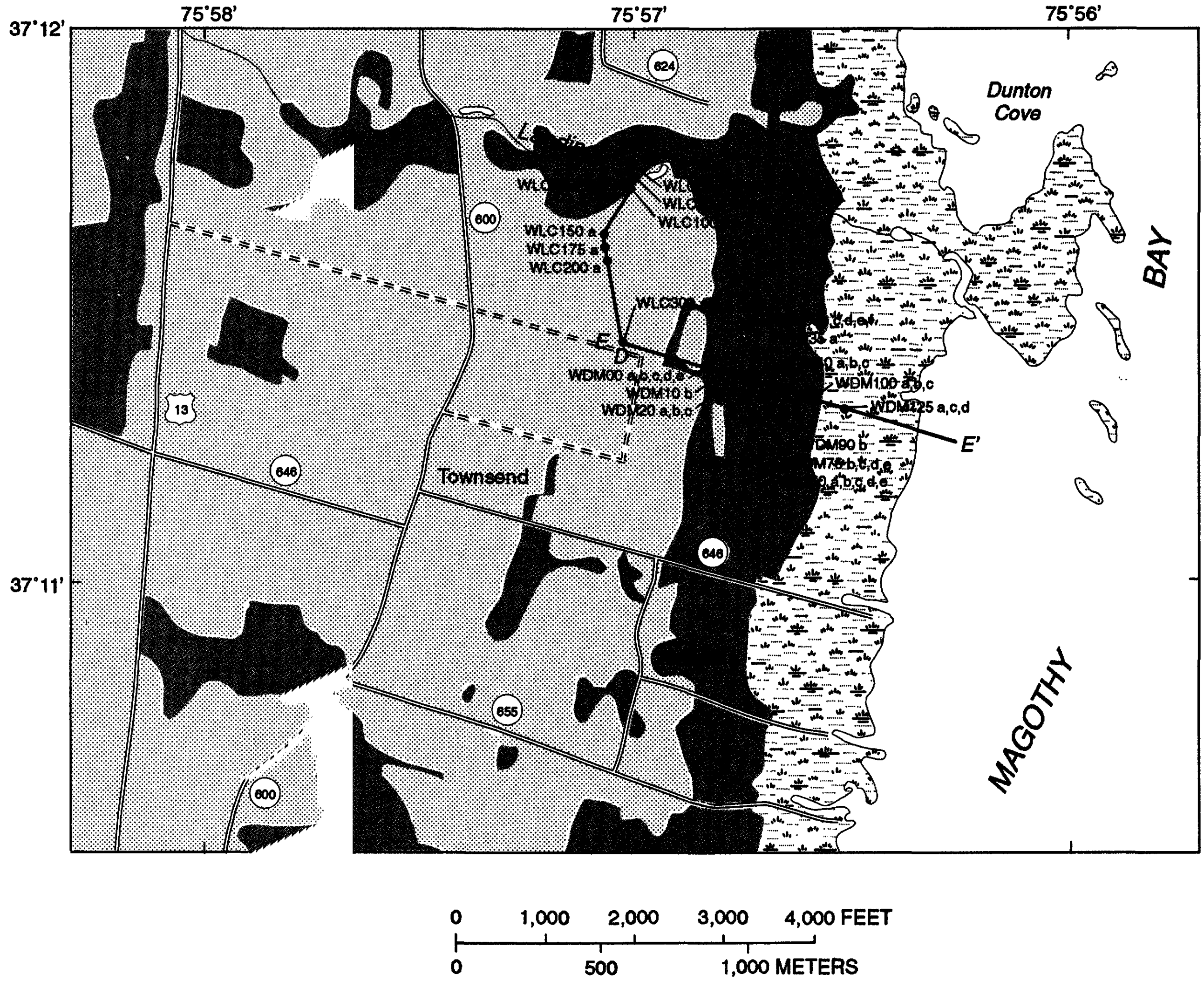
the southern tip of the Eastern Shore (figs. 1 and 7). The site consists of broad fields that extend eastward about 7,000 ft from the center of the peninsula to a scarp from which a 2,500-ft-wide riparian woodland and saltwater marsh sequence extends to Magothy Bay. A combination of soybeans, potatoes, and other crops were raised in the fields in the late spring, summer, and early fall; wheat was raised in the late fall, winter, and early spring. Few, if any, ditches are needed to drain the fields in order to raise the crops even though the fields are large and natural surface drainage is poorly developed. Although a transect of well clusters and individual wells extends from the center of the peninsula into the saltwater marsh, the area of emphasis in this report is from a cluster in the field about 1,000 ft from the edge of the woodlands (cluster WLC300) through the woodlands and into the saltwater marsh (Section *E–E′* (fig. 7)). Individual wells and clusters of three to five wells are located at 12 locations along this transect. The transect is located about midway between two nontidal creeks that are about 1 mi apart. These creeks are bordered by riparian woodlands.

Land-surface altitude at the center of the peninsula is about 35 to 40 ft above sea level and gradually decreases to 28.5 ft above sea level at cluster WLC300. Land-surface altitude decreases to about 14 ft above sea level at the edge of the woodlands and continues to decrease to about 5 ft above sea level 400 ft into the woodlands. Land surface changes are small beyond this point but appear to be important to the ground-water flow and distribution of plant types and their size. Land-surface altitude changes little to about 600 ft into the woodlands then rises about 1 ft (about 6 ft above sea level) before dropping 1 to 2 ft about 900 ft into the woodlands. Land-surface altitude changes little, remaining about 4.5 ft above sea level, until about 1,200 ft into the woodlands where it rises about 1 ft then gradually decreases to 4 ft above sea level between 1,400 and 1,500 ft into the woodlands. At this point, land cover changes from the woodlands to the saltwater marsh. About 200 to 300 ft into the marsh, a line of small wooded hummocks is oriented parallel to the edge of the woodlands and saltwater marsh. Otherwise, land-surface altitude changes little in the saltwater marsh until a small, but distinct, 1-ft scarp about 400 ft into the saltwater marsh (about 1,900 ft from the edge of the field). Land-surface altitude gradually decreases from 3 ft above sea level to sea level at Magothy Bay.

The small changes in land-surface altitude appear to contribute to changes in the vegetation in the woodlands and saltwater marsh. Mature pine trees dominate the canopy in the woodlands adjacent to the field before the first low flat area. This low area is a wooded wetland dominated by maples and other deciduous trees. Where the land surface first rises, a mixture of pine trees and maples predominates. The second low area is a dendritic wetland area with low wet areas surrounding large hummocks that rise from 1 to 2 ft above the low areas. In the low areas, 1 to 2 in. of organic material overlies fine-grained, gray silty sand. The sand appears to contain no live roots from the surrounding vegetation. The hummocks consist of a loose organic mixture of live roots and dead and decaying roots and other plant material having little mineral sediment. The altitude of the top of the sands beneath the hummocks is about the same as that of the sands beneath the low areas. Pines and myrtle predominate in this area and grow only on the hummocks. The pines are shorter and less dense than those in the adjacent woodlands. Growth of the pines appears to be stunted. In the last elevated area before the saltwater marsh, pines dominate the canopy. These trees are again more numerous and taller than those in the preceding low area. The height of these trees decreases toward the saltwater marsh. The first part of the saltwater marsh is dominated by dense marsh grasses about 3 to 4 ft tall. The hummocks in the saltwater marsh have a mixture of pines, myrtle, and red cedars. Sparse saltwater marsh grasses less than 1 ft tall dominate the marsh seaward of the small scarp.

The fields are underlain by sediments of the Butlers Bluff Member of the Nassawadox Formation to the west and the Joynes Neck Sand to the east, both consisting of coarse-grained sediments that contain little organic material. Soils beneath the fields are Bojac sandy loam, a deep, well-drained soil (Cobb and Smith, 1989). Sediments obtained from an auger hole at cluster WLC300 consisted of fine-grained to medium-grained, brown to tan sand from land surface (about 28.5 ft above sea level) to an altitude of about 14 ft below sea level. From 14 to 41 ft below sea level, sediments consisted of sandy, silty, clay alternating with zones of gravelly paleochannel deposits.

The large change in land-surface altitude near the edge of the fields and woodlands appears to be the scarp that forms the western edge of the Wachapreague Formation. Soils in the upper part of the



EXPLANATION

LAND USE AND COVER

Woodlands

Agriculture

Marsh

E —— E' LINE OF SECTION--Geohydrologic section

WDM40 a,b,c
• WELL CLUSTER--Letters and numbers are identification numbers for individual wells in cluster

WDM35 a
• SINGLE WELL--Letters and numbers are identification number

Figure 7. Locations of wells, well clusters, and other features at the site with coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh (Magothy Bay) and adjacent to a nontidal creek (Walls Landing Creek), Eastern Shore, Virginia.

Wachapreague Formation are the Nimmo sandy loam and the Magothy fine-grained sandy loam, both nearly level, very deep, and poorly drained soils. The small rise and fall in land-surface altitude beneath the woodlands and saltwater marsh probably are the surface expression of the sequences of beach ridges, cuspate spits, and lagoons that form the Wachapreague Formation (Mixon, 1985). At cluster WDM30 in the middle of the first wetland area (altitude about 5 ft above sea level), sediments varied from organic-rich peat to a plastic gray clay between land surface and an altitude of 2 ft below sea level. Based on additional borings, these sediments appear to be local deposits that only are present at the base of the scarp beneath the first wetland area; these sediments thin until they are absent about 200 ft from cluster WDM30 in either direction along the transect. Sediments from 2 to 9 ft below sea level were medium-grained to coarse-grained sand with layers of abundant large gravel. Sediments differ in color from red to brown, tan, and light gray. These sediments appear to be equivalent to the upper part of the Wachapreague Formation described by Mixon (1985). From an altitude of 9 to 19 ft below sea level (the bottom of the auger hole), sediments consisted of fine-grained to very fine-grained, gray to dark gray silty sand. These sediments appear to be equivalent to the lower 20-ft-thick lithologic unit of the Wachapreague Formation described by Mixon (1985). The 9 ft below sea level for the contact between these units at this site is similar to the 10 ft below sea level reported by Mixon (1985) for the type section. If the lower unit at this site is of a thickness similar to that observed by Mixon (1985), then the altitude of the bottom of the unit is about 30 ft below sea level. Based on altitudes of the various sediments, the upper sands and part of the clay and paleochannel sequence beneath the field appears to have been eroded from beneath the lowland area and replaced by sediments of the Wachapreague Formation.

The near-surface sandy sediments form the surficial aquifer at the site. Although the regional geohydrologic framework indicates that the bottom of the surficial aquifer is about 20 ft below sea level (Richardson, 1994), the bottom of the surficial aquifer beneath the fields is at the top of the clay and paleochannel sequence at 14 ft below sea level at cluster WLC300. Although the paleochannels will be grouped in the confining unit in this report, water can flow laterally in the coarse-grained parts of these sediments. Beneath the lowlands, the upper lithologic unit of the Wachapreague Formation is part of the surficial aquifer, but the geohydrologic role of the lower fine-grained unit is less clear. These fine-grained sediments do not inhibit vertical flow as much as the underlying confining unit, and do not allow lateral flow as much as the overlying aquifer. Wells open to these fine-grained sediments (wells WDM00e, WDM30e, WDM50e, and WDM75e) could be pumped dry at rates of less than 1 gal/min; wells open to the coarser overlying sediments could sustain such a pumping rate. The fine-grained sediments of the lower lithologic unit will be identified as a leaky confining unit in this report because of their flow-inhibiting and low water-yielding characteristics. Thus, the bottom of the surficial aquifer is about 14 ft below sea level beneath the fields and 9 ft below sea level beneath the lowland.

Walls Landing Creek

The site where ground water discharges to the nontidal creek (Walls Landing Creek) is located about 0.5 mi north of the wooded wetland and saltwater marsh site (Magothy Bay) (fig. 7); Walls Landing Creek lies to the north of the transect of wells that extends from the center of the peninsula to the saltwater marsh. A riparian woodland that has a maximum width of about 600 ft lies in the flood plain between the fields and the creek. A transect of individual wells and clusters of wells extends from Walls Landing Creek through a 250-ft-wide part of the woodland, through the fields, to cluster WLC300 (Section *D–D'*) in the Magothy Bay transect (Section *E–E'* (fig. 7)). Four clusters are located between the creek and the field: a cluster of five wells is located on the bank of the creek (cluster WLC00), a cluster of four wells is located half way between the creek and the field (cluster WLC50), a cluster of three wells is located half way between clusters WLC50 and the edge of the field (cluster WLC75), and a cluster of two wells is located at the edge of the field (cluster WLC100). Three individual wells are located along a dirt road through the fields between clusters WLC100 and WLC300 (wells WLC150a, WLC175a, and WLC200a).

Land-surface altitude changes little, gradually decreasing from 28.5 to 25.5 ft above sea level, in the approximately 1,500 ft between cluster WLC300 and well WLC175a. Altitude more rapidly declines to about 16.5 ft above sea level in the approximately 1,100 ft between well WLC175a and cluster WLC100 at the edge of the field. Altitude is about 14 ft above sea level at cluster WLC75, and it is 13 ft above sea level at clusters WLC50 and WLC00. The creek bed is about 12 ft above sea level.

Soils beneath the fields are primarily Bojac sandy loam, a nearly level, very deep, and well drained soil. The fields primarily are underlain by the Joynes Neck Sand although the Butlers Bluff Member of the Nassawadox Formation may lie beneath the fields near cluster WLC300. Both units contain coarse-grained sediments and contain little organic material. At cluster WLC100, sediment between land surface and a depth of 5 ft graded from a brown, medium-grained silty sand to a white, coarse-grained sand and gravel and contain large pieces of wood. In the flood plain, soils are Polwana loamy sand, a very deep, very poorly drained soil (Cobb and Smith, 1989). On the basis of land-surface altitudes commonly associated with these formations and those in the flood plain, the formations that lie beneath the flood plain could include a combination of Joynes Neck Sand, Wachapreague Formation, and recent alluvial deposits. At clusters WLC50 and WLC00 the upper 3 to 4 ft of sediment consisted of dark brown, organic rich, fine-grained sand, silt, and clay. These sediments do not resemble the sediments of either the Joynes Neck Sand or the upper part of the Wachapreague Formation that were obtained elsewhere in the area. The upper 3 to 4 ft of sediments could have been deposited in the ancient Walls Landing Creek drainage basin that may have existed at the time that sediments of the Wachapreague Formation were deposited. Below a depth of 3 to 4 ft to a depth of about 10.5 ft, sediments become fine-grained to coarse-grained, tan to light-tan sand and contain abundant gravel; some zones were more than 50 percent gravel. These sediments are similar in composition to those in the upper part of the Wachapreague Formation described by Mixon (1985), and to those encountered in the auger hole at cluster WDM30 on the nearby Magothy Bay transect. In augering to a depth of 10.5 ft, the altitude of the bottom of the auger hole was 1 to 2 ft above sea level, about 10 ft above the depth at which the fine-grained sediments of the lower part of the Wachapreague Formation were encountered at cluster WDM30.

The near-surface sandy sediments form the surficial aquifer at the site. Although the regional geohydrologic framework indicates that the top of the underlying confining unit is about 20 ft below sea level (Richardson, 1994); the top of the confining unit beneath the field is about 14 ft below sea level based on the auger hole at cluster WLC300.

Geochemical Reactions Affecting Water Quality

Numerous reactions can affect nitrogen geochemistry in ground-water systems. These primarily are oxidation-reduction reactions and generally are mediated by specific types of bacteria. Nitrogen is usually present in the environment in several forms, including nitrogen gas, organic nitrogen, ammonium, nitrite ions, and nitrate ions.

Nitrogen gas is present in the atmosphere, in ground water as a result of contact with the atmosphere before the water recharges the aquifer, and in ground water as a result of geochemical reactions that produce nitrogen gas. Organic nitrogen that is dissolved in ground water is provided by naturally occurring organic material, animal and human waste, and the application of organic fertilizers. When organic material decomposes, organically bound nitrogen is mineralized to form ammonia (NH_3). The reaction for the mineralization of urea (NH_2CONH_2), a simple form of organic nitrogen (Mitsch and Gosselink, 1993), is

$$NH_2CONH_2 + H_2O = 2NH_3 + CO_2 . \qquad (1)$$

Mineralization takes place in the presence or absence of dissolved oxygen (in aerobic and anaerobic environments, respectively) because no oxidation or reduction of the nitrogen takes place. In an aqueous environment, ammonia hydrolyzes to form ammonium hydroxide (NH_4OH); most of which ionizes to ammonium ion (NH_4^+) and hydroxyl ion (OH^-) in the pH range typically found in most geohydrologic systems, resulting in a net rise in pH. The hydroxyl ion reacts with dissolved carbon dioxide (CO_2) to form bicarbonate ion (HCO_3^-) as a part of the carbonate equilibria with a net reaction (Drever, 1988):

$$NH_3 + H_2O + CO_2 = NH_4^+ + HCO_3^- . \qquad (2)$$

Sources of organic nitrogen typically are sources of ammonium, also.

In an anaerobic environment, ammonium ion will remain as ammonium ion. As a positively charged ion, much of the ammonium, however, is immobilized by cation exchange onto negatively charged silt and clay particles. Algae, plants, and anaerobic microorganisms also can take up ammonium and convert it back to organic nitrogen; thus, ammonium serves as a nutrient for growth (Mitsch and Gosselink, 1993).

In an aerobic environment, ammonium ion is oxidized in a bacterially mediated, two-step process called nitrification. In the first step of the nitrification process, ammonium is converted to nitrite ion (NO_2^-) by *Nitrosomonas* sp:

$$2NH_4^+ + 3O_2 = 2NO_2^- + 2H_2O + 4H^+ + \text{energy}. \quad (3)$$

Nitrite is then converted to nitrate ion (NO_3^-) by *Nitrobacter* sp (Mitsch and Gosselink, 1993):

$$2NO_2^- + O_2 = 2NO_3^- + \text{energy}. \quad (4)$$

Because of the rapid progress of the second reaction in the nitrification process, the concentration of nitrite typically is near the detectable concentration in most natural systems. In addition to nitrification of ammonia, direct application of nitrate as a fertilizer for agricultural fields and lawns is another common source of nitrate. As a negatively charged ion, nitrate is very mobile in natural systems and can be readily leached from soils if not used by plants. As indicated by the production of hydrogen ion (H^+) in equation 3, nitrification is an acid-producing process. Thus, nitrification is one of the acid producing reactions that requires the addition of lime to adjust the pH of agricultural fields and lawns. A comparison of equations 2 and 3 shows that twice the amount of hydrogen ion is produced by nitrification than can be consumed by the bicarbonate ion formed by the hydrolysis of ammonia.

In ground-water systems where the concentration of dissolved oxygen is no longer sufficient for aerobic decomposition of organic material, nitrate is used by bacteria to decompose the organic material (Stumm and Morgan, 1981). Under such conditions, nitrate is chemically reduced by one of two processes: (1) denitrification to nitrogen gas; (2) dissimilatory nitrogen reduction to ammonium. In denitrification, a complex series of reactions oxidize organic material and convert nitrate to nitrogen gas. A simple form of the equation is (Stumm and Morgan, 1981):

$$\underset{\text{organic}}{5C} + 4NO_3^- + 4H^+ = 2N_2 + 5CO_2 + 2H_2O. \quad (5)$$

The resulting nitrogen gas is no longer available to most organisms as a nutrient source and, therefore, does not contribute to the eutrophication of aquatic systems. Intermediate nitrogen forms include nitrite, nitric oxide, and nitrous oxide. Denitrification appears to be the most commonly identified mechanism for nitrate reduction. Where dissimilatory reduction to ammonium is significant, the nitrogen remains available as a nutrient for possible eutrophication of aquatic systems but can be immobilized by cation exchange on silt and clay particles.

Nitrogen gas can be converted to other nitrogen species by certain blue-green algae and bacteria. The bacteria commonly live symbiotically on the roots of selected plants that include black locust trees and legumes, such as soybeans. In this way, these plants can also be sources of nitrogen to ground water.

Acknowledgments

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METHODS OF INVESTIGATION

Wells were constructed by hand-augering through the surficial sediments to the water table. A 2-in.-diameter screen and stainless-steel or galvanized-steel casing were then driven to selected depths by use of a two-person, hand-held hammer. Screens were 2.6-ft-long stainless-steel, wire-wound drive points with 0.010-in.-wide openings. As the deepest well at each cluster was driven, water was pumped with a centrifugal at approximately 2.5-ft intervals to determine how well each interval would yield water. Water samples were analyzed for specific conductance. In some instances the conductivity probe was lowered into the well, and specific conductance was measured at the top and bottom of the screen.

Specific conductance was used to identify vertical and lateral differences in water quality. This information was used to select the depth for completion of other wells at the cluster and the locations of additional well clusters. Existing wells of similar construction and lithologic descriptions from auger holes were available for the wooded-wetland and saltwater-marsh site (Magothy Bay) and the nontidal-creek site (Walls Landing Creek). Wells were first installed and data collected at the wooded-wetland and saltwater-marsh site to better understand processes and help design the well networks at other sites.

Holes also were hand augered below the water table at the well cluster in the first wooded wetland at the wooded-wetland and saltwater-marsh site and at the cluster on the creek bank at the nontidal-creek site to determine the lithology and organic content of the sediments. This was done by augering through a 4-in.-diameter polyvinylchloride (PVC) casing to prevent collapse of the hole while augering through saturated sediments. As the hole was deepened, the casing was driven deeper so that undisturbed sediments could be obtained. The lithology of the sediments was described. Selected samples were analyzed for inorganic carbon and total carbon content at the USGS National Water Quality Laboratory in Arvada, Colo. The organic carbon content of the sediments was calculated by difference. Holes were augered to a depth where sediments below the casing became a slurry and rose in the casing. These depths were 23.5 ft at the wooded-wetland site and 10.6 ft on the bank of the nontidal-creek site.

Water levels were periodically measured to the nearest 100th of a foot by use of a steel tape to determine seasonal changes in horizontal and vertical hydraulic gradients. Water levels were measured a minimum of two times in each well during each measurement period, and the altitude of each water level was compared to the altitude of water levels in other wells at the cluster to identify possible errors in measurement. Water levels were measured continuously in selected wells at the wooded-wetland and saltwater-marsh site (Magothy Bay) to provide greater detail in seasonal changes and daily cycles in water levels.

Wells were periodically bailed or pumped and specific conductance of the water was measured adjacent to the top and bottom of well screens. In some instances, the pH and the concentration of dissolved oxygen of the water were measured to compare seasonal changes to lateral and vertical differences in their values. Water samples were collected from wells at the wooded-wetland and saltwater-marsh site in September 1991. Water was pumped from the wells by use of a peristaltic pump until specific conductance, pH, and the concentration of dissolved oxygen stabilized. These properties and constituents were considered stabilized when systematic increases or decreases ceased and values remained constant or appeared to vary randomly. Samples were analyzed for nutrient and major-ion concentrations. Water samples were collected from all wells in August 1993 using the same methods as in September 1991. Samples from all wells were analyzed for nutrient concentrations and field-measured properties. Samples from selected wells were analyzed for nutrient and major-ion concentrations at the USGS National Water Quality Laboratory in Arvada, Colo.

Additional samples, collected in August 1993, were analyzed for chlorofluorocarbons (CFC's or freon) to determine the year in which the water recharged the aquifer, using collection methods described by Busenberg and Plummer (1992). Three types of CFC's were measured: trichlorofluoromethane (CCl_3F, referred to as CFC-11), dichlorodifluoromethane (CCl_2F_2, referred to as CFC-12), and trichlorotrifluoroethane ($C_2Cl_3F_3$, referred to as CFC-113). Samples from selected wells also were analyzed for dissolved gases to determine the recharge temperature for use in determining when the water recharged the aquifer (Busenberg and Plummer, 1992). Gas analyses also were used to identify samples in which denitrification produced nitrogen gas (eq. 5) by comparing concentrations of dissolved nitrogen and argon. The concentration of each CFC was used to develop a "modeled recharge date" of the water. The modeled recharge date represents the year when water at the base of the unsaturated zone became isolated from the soil atmosphere as it entered the saturated zone (Busenberg and Plummer, 1992). Water from several wells had been previously analyzed for CFC's (Dunkle and others, 1993); these values also are used in this report. Because water samples were collected at different times, the term "age" will be used to provide a uniform basis for comparison of data from all wells. Age is the difference in years between the modeled recharge date and the time the sample was collected. The CFC-12-based age is used in discussions in this report because CFC-11 degrades more rapidly in the low oxygen concentration present in water from many of the wells (Dunkle and others, 1993), and the maximum possible CFC-113-based age is less than the maximum possible CFC-12-based age. Ages are accurate within 2 years (Busenberg and Plummer, 1992).

Ground-water-recharge rates were estimated from the age of the ground water for wells at clusters that were located in recharge areas based on vertical hydraulic gradients. The use of this calculation assumes vertical flow. This is a valid assumption at, or near, the water table (Reilly and others, 1994). The distance, in inches, between the middle of the well screen and the water table (the middle of the screen for the adjacent well when calculating the recharge rate for the interval between two wells) was divided by the age of the water (difference in age of the water from the two wells). This value was multiplied by a porosity of 0.35—a typical porosity for sand (Walton, 1970)—to estimate the ground-water-recharge rate.

Several calculations can be used to estimate components of a water budget for an area, or otherwise develop insights about the ground-water-flow system. Commonly used ground-water concepts and calculations are the rate of ground-water flow through an aquifer; the depth to salty water in a water-table aquifer. A less commonly used ground-water calculation is the rate of evapotranspiration from daily changes in water levels.

The rate of ground-water flow through an aquifer can be calculated by Darcy's Law (Freeze and Cherry, 1979). This law assumes uniform hydraulic characteristics of the aquifer and a uniform gradient in the water table in a water-table aquifer. Discharge is calculated by the equation

$$Q = KiA, \tag{6}$$

where Q is the rate of flow through the aquifer, K is the hydraulic conductivity of the aquifer sediments, i is the hydraulic gradient (change in the level of the water table over a distance), and A is the area of the aquifer through which the water flows.

The Ghyben-Herzberg relation, based on the density of freshwater and salty water, is used to estimate the depth to salty water in a water-table aquifer that is under hydrostatic conditions (equilibrium conditions from a hydrologic perspective) (Freeze and Cherry, 1979). On the basis of ratio of the density of undiluted seawater to the density of freshwater, the calculated depth of saltwater in a water-table aquifer is 40 ft below sea level for every 1 ft that the water table rises above sea level. If the density of salty water is half that of seawater, the calculated depth to salty water is 20 ft. The depth of saltwater calculated by this relation typically underestimates the actual depth to saltwater in most situations, because systems generally are not under the assumed hydrostatic conditions (Freeze and Cherry, 1979).

White (1932) describes a method for calculating rates of evapotranspiration from ground water by using water-level hydrographs. Daily rates of evapotranspiration were calculated by the formula

$$q = S_y(24r + s), \tag{7}$$

where q is the depth of the water withdrawn by evapotranspiration over an area (in inches), S_y is the specific yield of the sediments (dimensionless), r is the hourly rate of change in ground-water levels when effects of evapotranspiration are minimal (in inches per hour), and s is the net fall (positive) or rise (negative) in the water table during a 24-hour period (in inches). A specific yield of 0.1 was used (a low value for the normal range in specific yield of sands of 0.1 to 0.3 (Walton, 1970)) because the shallow sands through which the ground-water levels normally fluctuate tend to be finer grained than deeper sands as a result of the greater weathering of the shallow sands; fine sand may not fully drain and would yield less water over the several hours of water-level changes than coarse sand. A 12-hour period from 8:00 p.m. to 8:00 a.m. was used to estimate the hourly rate of ground-water inflow in order to average inflows over as long a period as possible during times when the effects of evapotranspiration were small.

GEOHYDROLOGY AND GEOCHEMISTRY NEAR COASTAL GROUND-WATER-DISCHARGE AREAS

The surficial aquifer and confining units at each study site contain local variabilities superimposed on regional patterns in geohydrologic and geochemical systems. Ground-water flow at each site is a combination of local and regional flow, or is dominated by local flow. Ground-water levels and flow through the surficial aquifers are controlled by seasonal and spatial differences in recharge to, and discharge from, the aquifer. Ground-water levels rise as a result of recharge during the winter and early spring when rates of evapotranspiration are low. Ground-water levels decline when evapotranspiration increases to maximum rates in the late spring and summer; most of the precipitation that falls on the Eastern Shore during these periods replaces moisture deficits in the unsaturated zone, and little water recharges the surficial aquifer. Horizontal hydraulic gradients are from the central uplands where recharge predominates toward the nontidal and tidal creeks, wetlands, and estuaries. Ground water can recharge or discharge in these areas depending on local hydrologic conditions.

Geohydrologic and geochemical information help explain the effects of ground-water flow and chemistry on the distribution of nitrate that is discharged to nontidal and tidal creeks, wetlands, and estuaries. The geohydrologic information helps determine the direction that ground water flows and transports nutrients and other dissolved constituents. Specific conductance and concentrations of nutrients and major ions reflect the combined effects of land use, geohydrologic conditions, and geochemical processes on nutrient distributions, and can indicate water sources.

The discussion for each site consists of three sections: geohydrology, geochemistry, and their implications for land-use management practices. The geohydrology is discussed first because of its effect on nitrate chemistry and transport. Water chemistry is briefly discussed in the geohydrology section because it assists in understanding ground-water flow. The geochemistry is then discussed in relation to land use, the geohydrology, and the concentrations and loads of nitrate in ground-water discharge. Finally, the implications of the geohydrology and geochemistry on land-use management practices are discussed.

Ground Water Discharging from Fine-Grained Upland Sediments to an Estuary (Leatherberry Creek)

Differences in grain size and organic content of the sediments at the Leatherberry Creek site create local differences in the geohydrology and geochemistry that are superimposed on the effects of land use. Effects of grain size on sediment permeability affect ground-water-recharge rates, water levels, and ground-water-flow rates. Differences in the organic

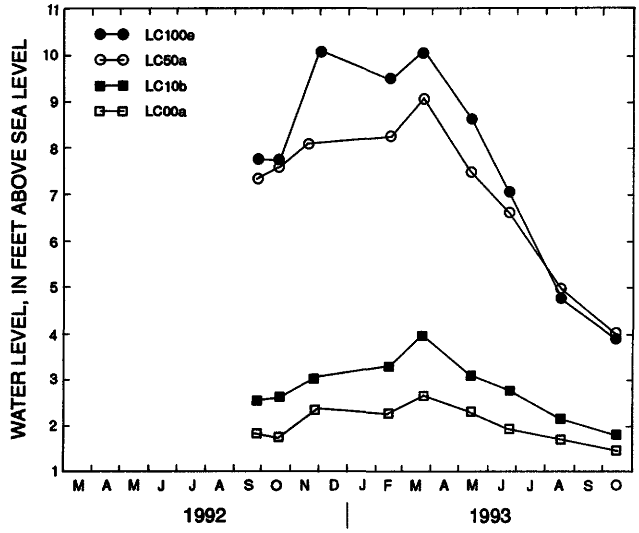


Figure 8. Water levels in selected wells at the site with fine-grained upland sediments adjacent to an estuary, Eastern Shore, Virginia.

content of the sediments create differences in concentrations of dissolved oxygen and nitrate.

Geohydrology

Ground water predominantly flows along local flow paths because upland sediments are deeply incised by the tidal creeks that form the local peninsula and because the interior of this peninsula is less incised by the numerous natural drainages and drainage ditches. Ground water flows from the center of the local peninsula to the tidal creeks, other natural drainages, and drainage ditches. The deep incisement of the tidal creeks and low relief in upland land surfaces limit ground-water flow through the surficial aquifer from the center of the main Eastern Shore peninsula to the tidal creeks.

Ground-water levels at the Leatherberry Creek site reflect the seasonal effects of recharge to, and discharge from, the ground-water system that are typical of the Eastern Shore (fig. 8). Standing water in parts of the interior woodlands during the winter appeared to reflect the altitude of the water table. Ground-water levels ranged from about 10 ft above sea level during the winter to about 4 ft above sea level during the early fall in wells at cluster LC100. Ground-water levels also approached land surface beneath the fields during the winter with water in the ditches nearly at field-surface levels (cluster LC50).

Water levels ranged from about 9 ft above sea level during the winter to about 4 ft above sea level during the early fall in wells at cluster LC50. Ground-water levels in wells at clusters LC10 and LC00 have similar seasonal patterns but were deeper beneath land surface and closer to sea level because these clusters are close to where ground water discharges to Leatherberry Creek. Water levels ranged from about 4 to 2 ft above sea level at cluster LC10 and 2.6 to 1.2 ft above sea level at cluster LC00 during the winter and fall, respectively.

Vertical hydraulic gradients were generally downward in all clusters (fig. 9), indicating that all clusters are in a recharge area. The greatest vertical gradients generally were at clusters LC50 and LC10 where gradients were downward from 0.0125 to 0.0590 between the water table and deepest well at each cluster. The ground-water divide between Leatherberry Creek and Chesapeake Bay appeared to be in the vicinity of cluster LC50 and well LC51a as indicated by the altitude of the water table. Although water at cluster LC50 may not always flow toward Leatherberry Creek, the quality of water from wells from this cluster probably is similar to the quality of water that drains to Leatherberry Creek from beneath fields that overlie the fine-grained sediments that contain abundant organic material. Vertical hydraulic gradients at cluster LC00 usually were downward and ranged from downward 0.0214 to upward 0.0193 (median 0.0157 downward). Although the cluster LC00 is only about 20 ft from Leatherberry Creek, the steep bank and the lack of wetlands and visible ground-water discharge also indicate that this cluster is located in a ground-water recharge area.

The age of the water increased with depth and ranged from less than 1 year in well LC10b to 38.5 years in well LC00d (ages are based on the most reliable age indicator, CFC-12; table 1, fig. 10). The young water extends deeper beneath the water table at clusters LC00 and LC10 than at clusters LC50 and LC100. The deeper young water probably results from greater recharge and more rapid flow of ground water through the coarse-grained sediments near the creek than through the fine-grained sediments away from the creek.

Rates of ground-water recharge estimated from ages ranged from 0.7 to 4.4 in/yr (table 1). These rates appear to be affected by the grain size of aquifer sediments through which precipitation recharged the aquifer (fig. 11). Recharge rates in the fine-grained

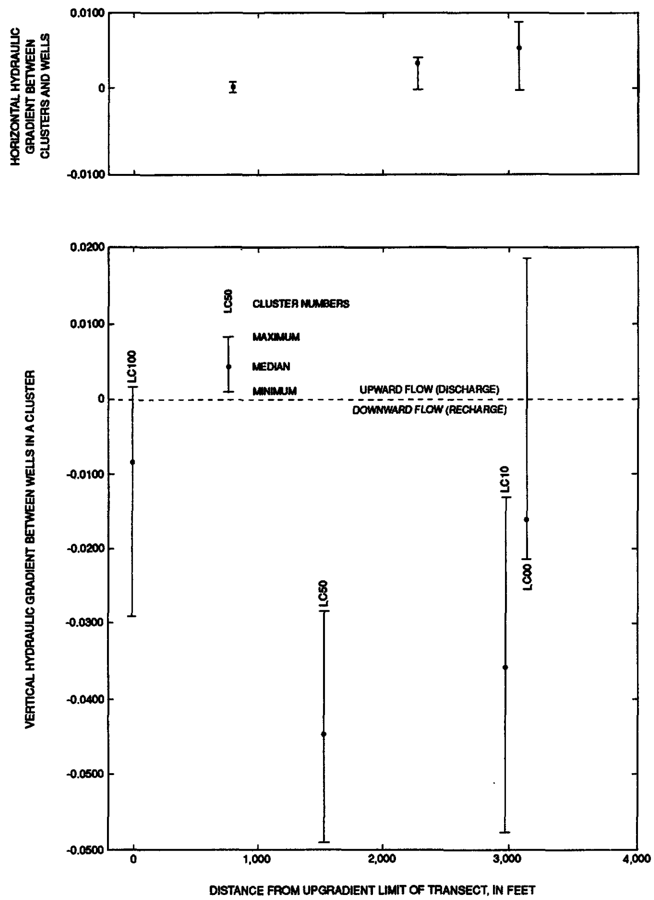


Figure 9. Horizontal and vertical hydraulic gradients at the site with fine-grained upland sediments adjacent to an estuary, Eastern Shore, Virginia. (Negative vertical gradients are downward and positive vertical gradients are upward.)

sediments beneath the center of the peninsula (clusters LC50 and LC100) were 0.9 to 2.3 in/yr. Recharge rates for water in deeper wells at clusters LC00 and LC10 (wells LC00c, LC00d, and LC10d) ranged from 0.7 to 2.0 in/yr. On the basis of concentrations of dissolved oxygen, nitrate, and other dissolved constituents, water from wells at clusters LC00 and LC10 was of a quality similar to that of water from wells at clusters LC50 and LC100 and appears to have recharged through the fine-grained sediments that contain abundant organic material. The median recharge rate for water through the fine-grained sediment was 1.4 in/yr. Recharge rates for water from shallow wells at these clusters (wells LC00a, LC00b, LC10b, and LC00c) were more than twice those of water from deeper wells, ranging from 3.2 to 4.4 in/yr with a median of 3.7 in/yr. The 3.2 in/yr value is for

Table 1. Ground-water age and annual recharge rates based on concentrations of chlorofluorocarbons (CFC's) in water from selected wells along transects in selected geohydrologic environments on the Eastern Shore, Virginia

[--, no data; >, greater than]

Local well number	Date	Well depth (feet)	Depth to water (feet)	Age (years)			Annual recharge rate (inch/year)
				CFC-11	CFC-12	CFC-113	
Fine-grained upland sediments adjacent to an estuary (Leatherberry Creek)							
LC100d	08-17-93	13.3	7.75	37.5	25.5	>27.5	0.9
LC50a	08-17-93	7.5	3.95	27.0	10.5	19.5	1.4
LC50d	08-17-93	19.7	4.67	39.5	32.5	26.0	2.3
LC10b	08-16-93	10.7	8.65	.0	.0	.0	[1]3.2
LC10c	08-16-93	13.8	8.93	5.0	3.5	2.0	3.7
LC10d	08-16-93	21.1	8.79	25.5	26.5	21.5	1.3
LC00a	08-17-93	5.3	1.91	4.0	2.0	.5	4.4
LC00b	08-17-93	10.2	1.69	10.0	7.5	8.5	3.7
LC00c	08-17-93	13.1	1.30	25.5	25.5	23.5	.7
LC00d	08-17-93	19.3	1.40	36.0	38.5	36.5	2.0
Coarse-grained upland sediments adjacent to an estuary (Cherrystone Inlet)							
CSF50a	08-10-93	7.9	5.96	6.5	3.5	4.5	--
CSF50b	08-10-93	11.3	5.94	5.5	2.5	1.5	--
CSF50c	08-10-93	14.3	5.80	6.0	2.0	4.0	--
CSF50d	08-10-93	22.0	6.09	20.0	19.0	19.0	--
CSF25b	08-11-93	10.5	7.25	5.5	3.0	4.0	--
CSF25c	08-11-93	13.5	7.40	--	--	--	--
CSF25d	08-11-93	17.9	7.31	17.0	13.5	15.0	--
CSF25d	08-11-93	22.6	7.25	19.7	17.5	18.5	--
CSW30a	08-12-93	10.8	7.84	5.0	3.5	5.0	--
CSW30b	08-12-93	13.0	7.84	5.0	.0	3.5	--
CSW30c	08-12-93	19.8	8.26	16.0	13.0	12.0	--
CSW30d	08-12-93	22.2	8.28	26.0	26.0	25.0	--
CSW10b	08-11-93	10.4	4.55	--	--	--	--
CSW10c	08-11-93	15.6	4.24	16.5	8.0	9.0	--
CSW10d	08-11-93	22.1	4.25	24.0	21.5	20.5	--
CSW00b	08-12-93	6.7	2.11	--	--	--	--
CSW00c	08-12-93	16.6	1.90	20.5	15.0	15.0	--
CSW00d	08-12-93	23.4	1.92	--	--	--	--
Coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh (Magothy Bay)							
WLC300e[2]	11-14-90	16.8	12.20	--	5.2	--	2.7
	04-05-91	16.8	10.69	--	2.0	--	5.9
WLC300b	11-14-90	26.0	12.20	8.0	8.1	--	13.3
	04-05-91	26.0	12.79	7.0	7.8	--	6.7
WLC300c	11-14-90	41.5	11.64	16.5	13.2	--	12.8
	04-05-91	41.5	12.20	14.8	13.0	--	12.5
WLC300d	11-14-90	61.5	12.27	32.6	35.2	--	--
	04-05-91	61.5	12.00	29.8	36.0	--	--
WDM00a	08-02-93	6.9	4.73	--	--	--	--
	08-05-93	6.9	4.81	--	--	--	--
WDM00b[2]	11-14-90	9.5	3.94	.6	5.7	--	3.1
	08-02-93	9.5	4.61	7.0	4.5	3.5	3.3
WDM00c	08-02-93	13.4	4.88	13.5	11.0	11.5	2.5
WDM00d	08-02-93	18.0	4.92	10.0	8.0	8.0	--

Footnote at end of table.

Table 1. Ground-water age and annual recharge rates based on concentrations of chlorofluorocarbons (CFC's) in water from selected wells along transects in selected geohydrologic environments on the Eastern Shore, Virginia—Continued

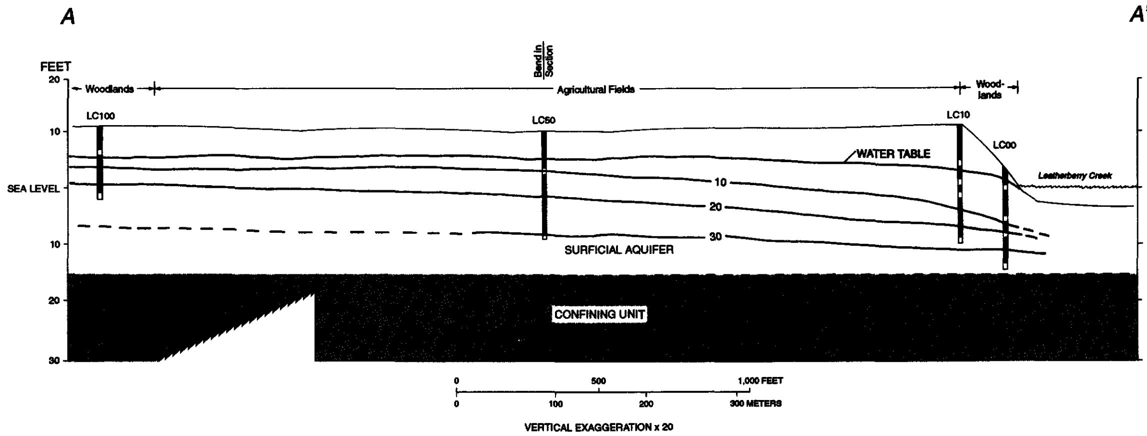
[--, no data; >, greater than]

Local well number	Date	Well depth (feet)	Depth to water (feet)	Age (years) CFC-11	Age (years) CFC-12	Age (years) CFC-113	Annual recharge rate (inch/year)
Coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh (Magothy Bay)—Continued							
WDM30b	08-05-93	7.6	2.37	--	--	--	--
WDM30c	08-05-93	10.7	2.31	15.5	11.5	11.0	--
WDM30d	08-05-93	15.0	2.61	32.5	37.5	>27.5	--
WDM30e	08-05-93	19.2	2.48	48.0	37.5	>27.5	--
WDM40b	08-04-93	7.4	4.54	26.0	24.5	21.5	--
	08-05-93	7.4	4.48	--	--	--	--
WDM40c	08-04-93	10.0	4.69	36.0	33.5	27.5	--
WDM50b	08-04-93	5.6	3.74	24.5	9.0	9.0	--
WDM50c	08-04-93	9.0	3.74	26.5	21.5	19.0	--
	08-05-93	9.0	3.98	--	--	--	--
WDM50d	08-04-93	13.0	3.59	36.0	43.0	>27.5	--
WDM50e	08-04-93	18.7	3.58	46	>53	>27.5	--
WDM75b	08-03-93	5.4	3.69	--	--	--	--
	08-05-93	5.4	3.81	--	--	--	--
WDM75c	08-03-93	9.0	3.71	43	34	26	--
WDM75d	08-03-93	13.2	3.63	54	39	27	--
WDM75e	08-03-93	17.2	3.43	42	45	>27.5	--
WDM90b	08-05-93	5.6	4.23	--	--	--	--
WDM100a	08-05-93	6.6	3.30	--	--	--	--
WDM125c	08-05-93	11.2	2.82	--	--	--	--
Coarse-grained upland sediments adjacent to a nontidal creek (Walls Landing Creek)[3]							
WLC175a	08-19-93	13.5	8.14	--	--	--	--
WLC150a	08-19-93	13.1	8.36	--	--	--	--
WLC100a[2]	08-18-93	8.9	3.83	6.0	3.5	4.0	--
	11-14-90	8.9	3.67	3.0	3.5	--	--
WLC100b	08-18-93	11.3	3.98	5.5	1.2	2.5	--
WLC50a	08-18-93	3.6	.95	43.0	20.0	>27.5	--
WLC50b[2]	08-18-93	6.6	1.36	17.0	16.5	16.0	--
	11-14-90	6.6	1.05	16.5	17.5	--	--
WLC50c	08-18-93	12.1	1.25	20.0	19.5	22.0	--
WLC50d	08-18-93	17.0	1.22	20.0	19.5	20.5	--
WLC00a	08-23-93	3.9	1.29	39.5	19.5	>27.5	--
WLC00b	08-23-93	7.4	1.23	29.5	11.5	24.5	--
WLC00c	08-23-93	8.8	1.13	36.5	13.0	--	--
WLC00d	08-23-93	14.9	1.13	42.5	13.5	27.5	--
WLC00e	08-23-93	18.2	.94	32.0	18.0	23.5	--
WDM00e[2]	11-14-90	28.0	3.94	14.6	14.2	--	9.1
	08-02-93	28.0	4.85	14.0	12.5	11.5	9.3
WDM20d	08-05-93	10.0	--	14.0	6.5	8.0	--

[1]This is a minimum recharge rate because water from the well was recharged the year the sample was collected. Recharge from that year possibly extended some distance below the well.

[2]Analyses from clusters WLC300 and wells WDM00b, WDM00e, WLC50b, and WLC100a that were not collected in 1993 are from Dunkle and others (1993).

[3]This transect also includes well cluster WLC300 in "Coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh."



EXPLANATION

—10 -- LINE OF EQUAL MODELED AGE--Dashed where approximately located. Interval, in years since recharged at the water table, is 10

WELL CLUSTER

LC100 Number

Cased part of wells

2.6-foot-long screened interval--Each screened interval is for a separate well in the cluster

Figure 10. Geohydrologic section showing ground-water age calculated from chlorofluorocarbon concentration at the site with fine-grained upland sediments adjacent to an estuary, Eastern Shore, Virginia. (Location of line of section shown on figure 5.)

water recharged during the year samples were collected; thus, this is a minimum recharge rate because additional water that recharged that year probably extends below the bottom of the well. On the basis of concentrations of dissolved oxygen, nitrate, and other dissolved constituents, water from shallow wells at clusters LC00 and LC10 was of a different quality than that from wells at clusters LC50 and LC100 and appears to have recharged through the overlying coarse-grained sediments that contain little organic material near Leatherberry Creek.

The variation in recharge rates probably results from the differences in (1) infiltration rates of the different grain-size sediments and (2) the depth to the water table. Infiltration rates are probably lower in areas underlain by fine-grained sediments and can cause greater surface runoff than from areas underlain by coarse-grained sediments. The standing water in the interior areas during the winter recharge period also can limit recharge to the ground water; much of the precipitation that falls on these saturated areas can drain to the tidal creeks as surface runoff, and ground water flows along short and shallow flow paths and discharges to the numerous natural drainages and drainage ditches. Shallow ground-water levels in interior areas during the early growing season also can increase the amount of ground water available to plants for evapotranspiration than is available near the tidal creeks. Therefore, evapotranspiration can provide a rapid discharge pathway for water that recharged the aquifer during the preceding winter recharge period. These differences in discharge pathways contribute to low rates of recharge of ground water that flows from the center of the peninsula to the tidal creeks. As rates of ground-water recharge decreased and rates of evapotranspiration increased through the spring and summer, ground-water levels declined below the bottoms of many of the natural drainages and drainage ditches, so that the predominant discharge to the surface waters shifted from the entire surface-drainage system to the more deeply incised tidal creeks.

The rates of ground-water recharge are less than, or in, the low part of the range of rates calculated from the base flow of streams throughout the Delmarva Peninsula that ranged from 3.5 to 16 in/yr (Cushing and others, 1973). The recharge rates probably are low because the hydrology of the site is not typical of the hydrology of many areas throughout

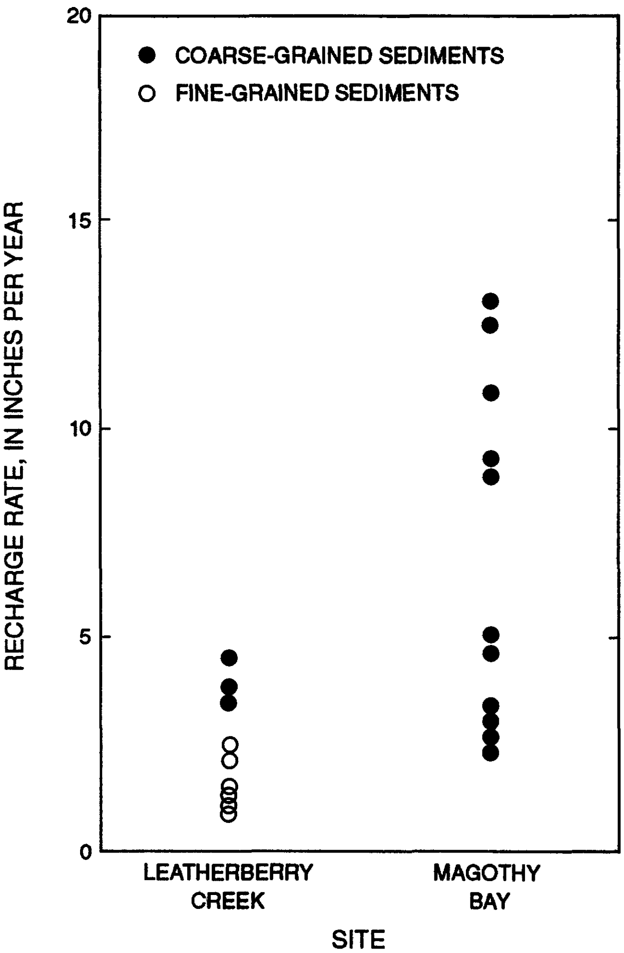


Figure 11. Ground-water recharge rates at selected well clusters on the Eastern Shore, Virginia.

the Delmarva Peninsula that are drained by nontidal creeks. Therefore, the rates of ground-water recharge and discharge calculated from the base flow of nontidal streams cannot necessarily be extrapolated to small, local areas, or to areas that directly discharge to tidal creeks and estuaries.

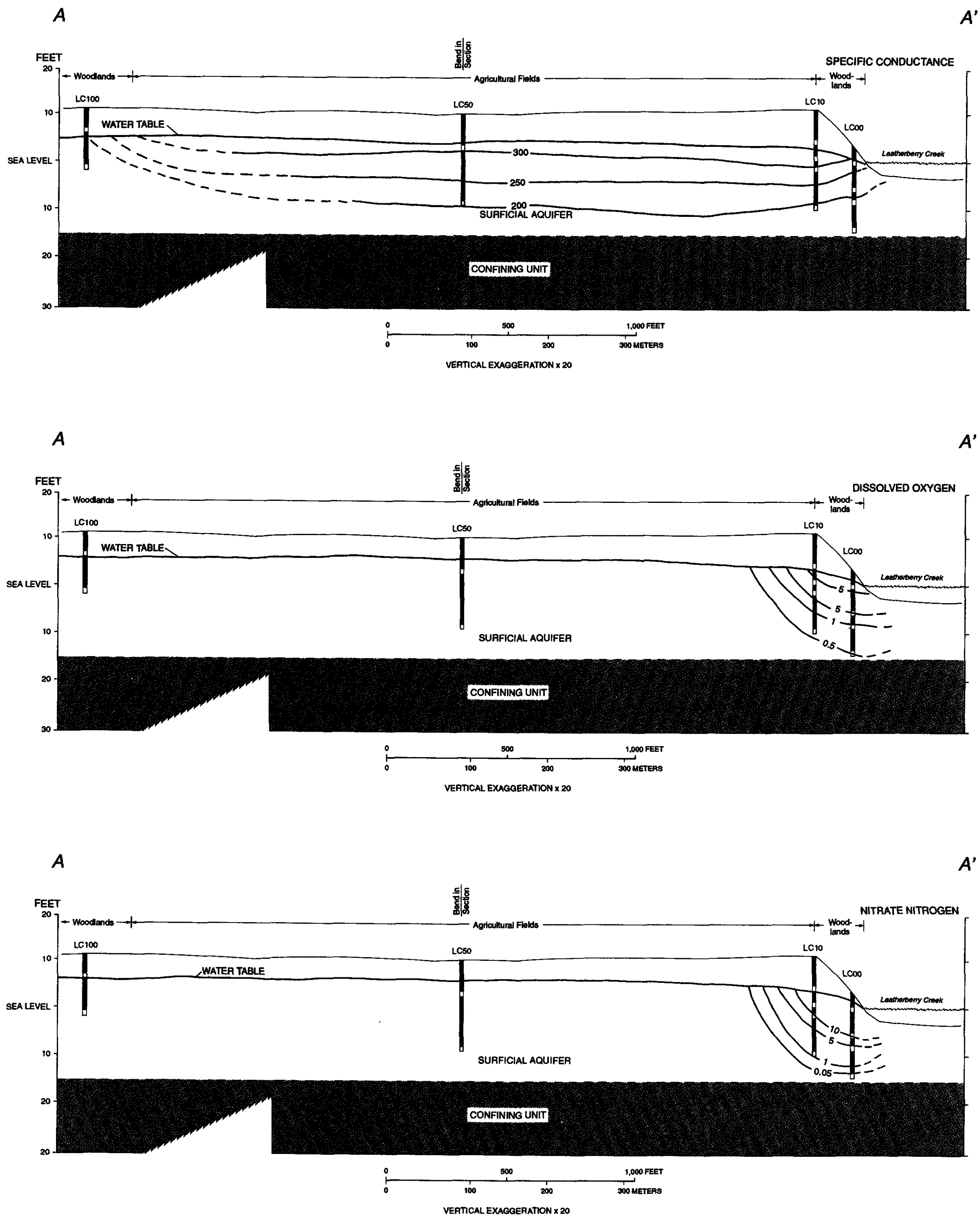
Although cluster LC00 is only about 20 ft from Leatherberry Creek, the deepest well at the cluster (LC00d) did not contain saltwater as indicated by the lack of saltwater in well LC00c (table 2) and by the similar specific conductance of water from wells LC00d and LC00c (table 3). The calculated depth to saltwater based on the Ghyben-Herzberg relation for well LC00d ranges from 48 to 104 ft below sea level. Consequently, salty water would not likely be in LC00d because the bottom of the well is only 16.5 ft below sea level. If the bottom of well LC00d is near the bottom of the surficial aquifer as indicated by the regional geohydrologic framework (Richardson, 1994) and the low yield of the well, saltwater probably is not present in the lower part of the surficial aquifer at this cluster.

Geochemistry

Water quality at the Leatherberry Creek site reflects the combined effects of agricultural practices and the effects of the geochemistry of water that recharged through the fine-grained, sediments that contain abundant organic material in the interior areas and the coarse-grained sediments that contain little organic material near Leatherberry Creek. Because ground water flows from the interior of the peninsula to the creek, deep ground water near the creek is older (fig. 10) and reflects the effects of earlier agricultural practices on the quality of water that was recharged beneath the interior of the peninsula. Differences in water quality form identifiable patterns in specific conductance; concentrations of dissolved inorganic ions, dissolved oxygen, and nitrate; and the relative composition of dissolved ions in the water; differences in specific conductance and concentrations of dissolved oxygen and nitrate, however, are emphasized in the discussion.

Specific conductance ranged from 175 to 336 µS/cm and differed between the shallow and deep wells, decreasing with depth at all clusters (fig. 12 and table 3). This difference between shallow and deep wells is contrary to the patterns that naturally exist in most ground-water systems, where specific conductance and concentrations of ions from geochemical reactions between water and minerals increase as water flows deeper and has been in contact with aquifer sediments for longer periods. Water from the deep wells appears to reflect the effects of older agricultural practices that apparently had less effect on ground-water quality. The specific conductance of 180 µS/cm in water from well LC100e is among the least of any well at the site and probably represents the background effects of recharge though the woodland on the quality of ground water. Although the altitude of land surface at cluster LC00 is near that of the

Figure 12. Geohydrologic section showing specific conductance and concentrations of dissolved oxygen and nitrate in ground water at the site with fine-grained upland sediments adjacent to an estuary, Eastern Shore, Virginia. (Location of line of section shown on figure 5.) ▶



EXPLANATION

—10 - - LINE OF EQUAL VALUE OF INDICATED VARIABLE--Dashed where approximately located. Interval is variable. Specific conductance is in microsiemens per centimeter at 25°C, dissolved oxygen is in milligrams per liter, and nitrate nitrogen is in milligrams per liter as nitrogen

WELL CLUSTER

LC100 Number

Cased part of wells

2.6-foot-long screened interval--Each screened interval is for a separate well in the cluster

Table 2. Concentrations of dissolved inorganic constituents in water from selected wells along transects in different geohydrologic environments on the Eastern Shore, Virginia

[mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than]

Local well number	Date	Well depth (feet)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Alkalinity (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Silica (mg/L)	Iron (µg/L)	Manganese (µg/L)
Fine-grained upland sediments adjacent to an estuary (Leatherberry Creek)												
LC100e	08-17-93	13.3	1.6	3.1	17	0.7	18	24	23	14	4,200	27
LC50a	08-17-93	7.5	29	9.9	8.2	.6	49	36	35	12	630	100
LC10b	08-16-93	10.7	36	8.5	6.1	.6	30	16	30	8.5	120	20
LC10c	08-16-93	13.8	25	7.3	5.7	.9	20	29	19	11	3	10
LC10d	08-16-93	21.1	8.8	4.8	12	1.1	15	27	17	17	22	6
LC00b	08-17-93	10.2	19	8.5	7.3	.8	16	29	17	12	12	5
LC00c	08-17-93	13.1	9.4	5.8	12	1.2	18	28	17	17	<3	6
Coarse-grained upland sediments adjacent to an estuary (Cherrystone Inlet)												
CSF50b	08-10-93	11.3	35	8.2	7.5	.4	36	43	16	5.4	110	6
CSF50d	08-10-93	22.0	38	36	14	2.7	30	160	41	19	25	17
CSF25b	08-11-93	10.5	32	7.9	6.9	.8	27	33	24	5.5	100	14
CSF25d	08-11-93	17.9	47	26	13	1.7	26	130	35	13	13	280
CSF25e	08-11-93	22.6	63	32	22	2.6	45	150	52	16	30	440
CSW30b	08-12-93	13.0	32	9.7	6.2	1.2	32	25	22	4.2	47	4
CSW30d	08-12-93	22.2	37	38	18	2.7	56	140	47	20	14	150
CSW10b	08-11-93	10.4	55	58	570	5.2	210	250	890	16	6,400	860
CSW10c	08-11-93	15.6	41	21	81	1.1	39	89	150	9.4	90	350
CSW00c	08-12-93	16.6	85	79	460	6.0	533	200	780	13	220	560
Coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh (Magothy Bay)												
WLC300a	08-16-88	16.8	29	5.8	9.6	8.5	4	49	28	7.0	1,300	25
	[1]09-05-91	16.8	42	7.1	31	11	5.3	49	85	7.3	18	16
WLC300b	08-16-88	26.0	40	6.1	6.5	6.1	4	68	21	9.1	40	19
	09-05-91	26.0	38	5.4	6.3	5.3	3.3	69	26	9.0	12	7
WLC300c	08-16-88	41.5	56	9.3	12	3.5	2.7	110	27	12	24	85
	09-05-91	41.5	56	9.5	11	4.1	5.3	110	27	11	16	18
WLC300d	08-16-88	61.5	47	3.3	10	1.3	65	67	24	13	33	77
WDM00b	08-17-88	9.5	35	6.0	7.3	4.8	15	54	22	6.3	92	9
	09-05-91	9.5	35	5.6	7.0	5.1	16	58	13	6.9	75	4
WDM00c	08-02-93	13.4	53	7.5	9.7	2.4	25	88	30	12	17	8
WDM00d	08-02-93	18.0	45	6.7	9.8	1.1	18	69	31	12	1,300	25
WDM00e	08-17-88	28.0	58	8.8	11	1.2	6	110	31	13	13	8
	09-05-91	28.0	56	7.7	10	1.3	4.5	120	31	14	28	7
WDM10b	09-05-91	7.0	45	7.5	17	10	45	88	55	6.3	3,600	140
WDM20b	09-05-91	6.6	45	8.4	20	14	33	97	60	6.2	900	23
WDM20d	08-05-93	10.0	37	6.1	11	11	25	66	30	6.2	77	14
WDM30b	09-05-91	7.6	41	8.8	9.8	4.7	16	96	36	13	10	10
WDM30c	09-05-91	10.7	42	12	12	4.6	16	96	36	17	13	2
WDM30d	08-05-93	15.0	39	4.1	14	1.4	46	72	21	18	2,100	120
WDM30e	09-05-91	19.2	44	3.2	13	1.3	63	65	24	15	11	92
WDM35a	09-05-91	4.2	47	13	14	2.7	8.2	110	35	16	260	13
WDM40b	09-05-91	7.4	38	16	17	2.4	9.8	110	33	20	32	3
WDM40c	08-04-93	10.0	36	9.5	13	1.6	26	100	22	22	19	3
WDM50b	09-04-91	5.6	37	19	33	--	23	150	51	23	1,900	16
WDM50c	09-04-91	9.0	33	14	21	--	15	99	29	22	43	7
WDM50d	09-04-91	13.0	39	4.6	17	--	36	73	19	23	43	51
WDM50e	08-04-93	18.7	30	1.8	10	.8	69	21	13	15	20	22

Footnote at end of table.

Table 2. Concentrations of dissolved inorganic constituents in water from selected wells along transects in different geohydrologic environments on the Eastern Shore, Virginia—Continued

[mg/L, milligrams per liter; µg/L, micrograms per liter; --, no data; <, less than; W.L. Creek, Walls Landing Creek]

Local well number	Date	Well depth (feet)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Alkalinity (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Silica (mg/L)	Iron (µg/L)	Manganese (µg/L)
Coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh (Magothy Bay)—Continued												
WDM75b	09-05-91	5.4	45	100	790	20	62	380	1,400	16	23,000	120
WDM75c	09-04-91	9.0	29	7.3	66	1.7	62	36	120	17	3,800	110
WDM75d	09-04-91	13.2	39	2.4	20	1.2	80	20	37	17	340	73
WDM75e	09-04-91	17.2	30	1.5	11	.96	69	17	24	15	94	26
WDM90b	09-04-91	5.6	28	71	650	22	44	210	1,200	13	8,100	44
WDM100a	08-16-88	6.6	100	170	1,100	20	62	340	2,000	16	4,200	53
	09-04-91	6.6	32	53	500	22	64	170	920	15	1,700	32
WDM100b	09-04-91	8.6	47	57	550	17	92	190	990	18	4,200	39
WDM125a	08-15-88	6.7	280	850	6,400	200	119	2,000	3,000	8.8	79,000	110
Coarse-grained upland sediments adjacent to a nontidal creek (Walls Landing Creek)[2]												
WLC100a	06-28-90	8.9	28	4.7	5.9	5.0	8	40	20	5.6	120	35
	08-18-93	8.9	52	11	12	8.7	7	61	47	6.6	22	37
WLC100b	08-18-93	11.3	50	9.4	11	7.6	11	42	46	6.3	33	21
WLC50a	08-18-93	3.6	49	13	20	1.8	82	84	40	19	6,100	62
WLC50b	06-28-90	6.6	52	19	12	1.6	43	91	30	13	17	1
WLC50c	08-18-93	12.1	65	16	12	1.6	57	100	27	15	27	4
WLC00a	08-23-93	3.9	82	12	14	3.4	116	120	27	13	20	13
WLC00c	08-23-93	8.8	84	14	15	5.6	120	130	30	7.1	24	6
WLC00e	08-23-93	18.2	78	14	13	4.1	107	150	29	11	15	20
W.L. Creek	08-23-93	--	52	11	12	3.5	26	97	27	11	38	10

[1] Sample appears to be affected by shell material laid on a driveway that covers part of the recharge area.

[2] This transect also includes well cluster WLC300 in "Coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh."

creek, specific conductance of the water indicates that water from the creek has minimal effect on the quality of the ground water at the cluster. Specific conductance of water from the creek was about 30,000 µS/cm, and specific conductance of the ground water ranged from 175 to 268 µS/cm.

The concentration of dissolved oxygen was 1.0 mg/L, or less, in water from wells in the fine-grained, sediments that contain abundant organic material in the interior of the peninsula (wells LC50a, LC50e, LC51a, and LC100e), even in wells open to the water table where the concentration of dissolved oxygen is usually the greatest (table 3 and fig. 12). The concentration of dissolved oxygen reflects the effects of decomposition of organic material and the resulting uptake of dissolved oxygen in the sediments that contain abundant organic material. The concentration of dissolved oxygen in water from shallow wells at the clusters in the coarse-grained sediments that contain little organic material (clusters LC00 and LC10) and from well LC52a ranged from 1.7 to 6.8 mg/L, reflecting the effects of lower rates of decomposition and the uptake of dissolved oxygen in these sediments. The concentration of dissolved oxygen, however, was less than 1 mg/L in the deepest wells in these clusters. This probably reflects the effects of recharge through the fine-grained sediments that contain abundant organic material in the interior of the peninsula based on the similarity in water quality; although, the downward flow of water from the shallow sediments that contain little organic material into the deeper sediments that contain abundant organic material and the greater residence time of the deeper ground water also are possible causes of the low concentration of dissolved oxygen.

Table 3. Specific conductance, pH, and concentrations of dissolved oxygen and nutrients in water from selected wells along transects in different geohydrologic environments on the Eastern Shore, Virginia

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25°Celsius; <, less than]

Local well number	USGS well number	Date	Well depth (feet)	Specific conductance (µS/cm)	pH (units)	Oxygen, dissolved (mg/L)	Nitrogen (mg/L)				Phosphorus (mg/L)	
							Nitrate	Nitrite	Ammonia	Organic	Dissolved	Dissolved, ortho
Fine-grained upland sediments adjacent to an estuary (Leatherberry Creek)												
LC100e	63K38	08-17-93	13.3	180	5.55	0.3	<0.05	<0.01	0.06	<0.2	<0.01	<0.01
LC50a	63K33	08-17-93	7.5	302	6.42	.39	<.05	<.01	.04	<.2	<.01	<.01
LC50e	63K34	08-17-93	19.7	242	6.31	.08	<.05	<.01	.20	.0	<.01	.01
LC51a	63K35	08-18-93	6.8	226	6.51	1.0	<.05	<.01	.52	.1	<.01	<.01
LC52a	63K36	08-18-93	6.8	257	6.05	5.7	8.3	<.01	.08	.4	<.01	<.01
LC10b	63K30	08-16-93	10.7	336	6.35	1.7	14	.01	.06	<.2	<.01	.03
LC10c	63K31	08-16-93	13.8	256	6.11	6.8	9.9	<.01	.05	<.2	<.01	<.01
LC10d	63K32	08-16-93	21.1	191	5.87	.67	2.6	.04	.05	<.2	<.01	<.01
LC00a	63K25	08-17-93	5.3	268	5.95	4.5	11	<.01	.06	<.2	<.01	<.01
LC00b	63K26	08-17-93	10.2	247	6.42	6.3	14	<.01	.02	<.2	<.01	.01
LC00c	63K27	08-17-93	13.1	188	6.18	1.21	2.7	<.01	.02	<.2	<.01	<.01
LC00d	63K28	08-17-93	19.3	175	6.32	.06	<.05	<.01	.17	<.2	.03	.05
Coarse-grained upland sediments adjacent to an estuary (Cherrystone Inlet)												
CSF50a	63G57	08-10-93	7.9	370	6.43	5.5	15	<.01	.03	<.2	<.01	.01
CSF50b	63G58	08-10-93	11.3	315	6.22	3.7	9.0	.01	.02	<.2	<.01	<.01
CSF50c	63G59	08-10-93	14.3	385	6.21	2.4	7.7	.03	.05	<.2	<.01	<.01
CSF50d	63G60	08-10-93	22.0	703	6.55	.4	14	.08	.02	<.2	<.01	<.01
CSF25b	63G62	08-11-93	10.5	298	6.14	5.4	9.2	<.01	.03	<.2	<.01	<.01
CSF25c	63G63	08-11-93	13.5	330	6.09	3.7	10	<.01	.01	.2	<.01	.01
CSF25d	63G64	08-11-93	17.9	628	5.87	.7	21	.08	.03	<.2	<.01	<.01
CSF25e	63G65	08-11-93	22.6	756	6.29	.04	27	.32	.14	.4	<.01	<.01
CSW30a	63G53	08-12-93	10.8	308	5.98	8.0	7.8	<.01	.04	.4	<.01	<.01
CSW30b	63G54	08-12-93	13.0	319	5.92	6.4	13	<.01	.03	<.2	<.01	<.01
CSW30c	63G55	08-12-93	19.8	473	5.99	1.4	12	.90	.23	.1	<.01	<.01
CSW30d	63G56	08-12-93	22.2	664	6.29	.3	17	.39	.05	<.2	<.01	<.01
CSW10b	63G50	08-11-93	10.4	3,640	6.72	.06	.13	.01	.07	.3	<.01	<.01
CSW10c	63G51	08-11-93	15.6	874	5.83	1.0	9.0	.01	.03	2.4	<.01	<.01
CSW10d	63G52	08-11-93	22.1	2,800	6.64	.7	9.0	.15	.07	.1	<.01	<.01
CSW00b	63G46	08-12-93	6.7	17,830	7.03	.2	.13	<.01	.43	.2	<.01	<.01
CSW00c	63G47	08-12-93	16.6	3,460	6.27	.05	8.0	.03	.03	<.2	<.01	<.01
CSW00e	63G48	08-12-93	23.4	3,060	6.6	.6	.39	<.01	.14	.3	<.01	<.01
C.S. Inlet[1]		08-23-93	--	37,700	7.76	6.1	<.01	<.01	.04	.2	<.01	<.01
Coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh (Magothy Bay)												
WLC300a	63F28	08-16-88	16.8	291	5.1	9.0	9.7	<.01	<.01	.4	--	<.01
		09-05-91	16.8	420	5.5	8.6	12	.001	<.002	.7	<.001	<.001
WLC300b	63F44	08-16-88	26.0	333	5.4	7.7	9.6	<.01	.01	.3	--	--
		09-05-91	26.0	320	5.6	8.3	9.7	.001	<.002	.6	<.001	<.001
WLC300c	63F45	08-16-88	41.5	431	6.2	5.1	9.2	<.01	.01	.5	--	--
		09-05-91	41.5	390	6.5	4.2	7.8	.001	<.002	.6	.002	.002
WLC300d	63F46	08-16-88	61.5	336	7.4	.4	.37	<.01	.02	.4	--	.06
WDM00b	63F29	08-17-88	9.5	311	5.2	8.5	8.9	<.01	<.01	.7	--	<.01
		09-05-91	9.5	280	5.9	4.8	8.0	.001	<.002	.7	<.001	<.001
		08-02-93	9.5	368	5.28	3.0	22	<.01	.01	<.2	<.01	.02
WDM00c	63F85	08-02-93	13.4	416	6.08	3.6	10	<.01	.02	<.2	<.01	<.01
WDM00d	63F86	08-02-93	18.0	379	6.01	8.7	9.9	<.01	.04	<.2	<.01	<.01

Footnote is at end of table.

Table 3. Specific conductance, pH, and concentrations of dissolved oxygen and nutrients in water from selected wells along transects in different geohydrologic environments on the Eastern Shore, Virginia—Continued

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25°Celsius; <, less than]

Local well number	USGS well number	Date	Well depth (feet)	Specific conductance (µS/cm)	pH (units)	Oxygen, dissolved (mg/L)	Nitrogen (mg/L)				Phosphorus (mg/L)	
							Nitrate	Nitrite	Ammonia	Organic	Dissolved	Dissolved, ortho
Coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh (Magothy Bay)—Continued												
WDM00e	63F47	08-17-88	28.0	462	5.1	8.6	11	<0.01	<0.01	0.8	--	--
		09-05-91	28.0	418	5.4	5.6	11	<.001	<.002	.6	.001	.001
		08-02-93	28.0	395	4.96	5.1	10	<.01	.01	<.2	<.01	<.01
WDM10b	63F57	09-05-91	7.0	450	6.2	.2	2.1	.069	.287	.3	<.001	<.001
WDM20b	63F58	09-05-91	6.6	470	5.9	.2	2.1	.017	.004	.3	.002	<.001
WDM20d	63F83	08-05-93	10.0	385	6.12	.7	5.3	<.01	.01	<.2	<.01	<.01
WDM30b	63F59	09-05-91	7.6	380	5.9	.6	5.6	.004	.005	.8	.014	.012
		08-05-93	7.6	--	--	--	7.0	<.01	<.01	<.2	<.01	.02
WDM30c	63F60	09-05-91	10.7	400	6.0	2.7	8.2	.001	<.002	<.2	.016	.013
		08-05-93	10.7	379	6.33	4.6	8.0	<.01	<.01	<.2	<.01	.02
WDM30d	63F80	08-05-93	15.0	324	7.38	.3	.42	<.01	.07	<.2	<.01	<.01
WDM30e	63F61	09-05-91	19.2	275	7.8	.2	.011	<.001	.011	<.2	.036	.033
		08-05-93	19.2	330	7.98	.01	<.05	<.01	.02	<.2	<.01	.03
WDM35a	63F62	09-05-91	4.2	445	5.3	1.8	5.6	.002	.013	.6	.009	.002
WDM40b	63F63	09-05-91	7.4	440	5.8	2.4	7.5	.003	<.002	.8	.011	.009
		08-04-93	7.4	415	5.86	1.5	3.7	<.01	.01	<.2	<.01	<.01
WDM40c	63F79	08-04-93	10.0	371	6.43	.30	1.3	.01	.01	<.2	<.01	.03
WDM50b	63F64	09-04-91	5.6	525	5.8	.2	1.2	.019	.015	.3	.004	<.001
		08-04-93	5.6	760	5.90	.04	1.1	.02	.06	<.2	<.01	<.01
WDM50c	63F65	09-04-91	9.0	388	6.2	.4	3.8	.016	<.002	.4	.024	.023
		08-04-93	9.0	500	6.20	.2	2.1	.02	<.01	<.2	<.01	.02
WDM50d	63F66	09-04-91	13.0	315	7.4	.4	.171	.003	.007	<.2	.035	.036
		08-04-93	13.0	342	6.95	.2	.078	<.01	<.01	<.2	<.01	.01
WDM50e	63F77	08-04-93	18.7	225	7.14	.5	<.05	<.01	.02	<.2	.08	.08
WDM75b	63F67	09-05-91	5.4	4,950	5.8	.2	.19	.007	.736	.4	.077	.071
WDM75c	63F68	09-04-91	9.0	600	6.7	.05	<.005	.003	.115	<.2	.095	.090
		08-03-93	9.0	791	6.95	.1	<.05	<.01	.09	<.2	.05	.04
WDM75d	63F69	09-04-91	13.2	320	7.0	.1	.007	.001	.032	<.2	.052	.045
		08-03-93	13.2	325	6.83	.1	<.05	<.01	.05	<.2	.04	.06
WDM75e	63F70	09-04-91	17.2	210	8.1	.1	.020	.001	.032	<.2	.060	.059
		08-03-93	17.2	234	8.09	.1	<.05	<.01	.04	<.2	.04	.05
WDM90b	63F71	09-04-91	5.6	3,800	5.8	.2	<.05	.005	.619	.8	.019	.016
WDM100a	63F40	08-16-88	6.6	6,610	5.5	.8	<.01	<.01	.21	.1	--	.06
		09-04-91	6.6	3,350	6.1	.02	.003	.002	.08	.5	.047	.042
WDM100b	63F72	09-04-91	8.6	3,510	6.4	.2	.062	.002	.062	.4	.092	.083
WDM125a	63F41	07-21-92	--	28,600	--	--	--	--	--	--	--	--
Coarse-grained upland sediments adjacent to a nontidal creek (Walls Landing Creek)[2]												
WLC100a	63F26	06-28-90	8.9	--	--	5.4	6.6	--	<.01	--	--	--
		11-14-90	8.9	--	--	3.8	13	--	<.01	--	--	--
		08-18-93	8.9	514	5.49	5.1	21	<.01	.02	<.2	<.01	<.01
WLC100b	63F98	08-18-93	11.3	468	5.86	5.7	21	<.01	.03	<.2	<.01	<.01
WLC50a	63F92	08-18-93	3.6	488	6.22	.02	<.05	<.01	.91	.9	.19	.18
WLC50b	63F25	06-28-90	6.6	--	--	6.3	14	--	<.01	--	--	--
		11-14-90	6.6	--	--	3.8	13	--	<.01	--	--	--
		08-18-93	6.6	496	6.87	5.8	12	<.01	.02	<.2	.01	.01
WLC50c	63F93	08-18-93	12.1	542	6.91	5.7	9.7	<.01	.04	<.2	<.01	<.01
WLC50e	63F94	08-18-93	17.0	587	7.13	4.4	11	.01	.05	<.2	<.01	<.01

Footnote is at end of table.

Table 3. Specific conductance, pH, and concentrations of dissolved oxygen and nutrients in water from selected wells along transects in different geohydrologic environments on the Eastern Shore, Virginia—Continued

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25°Celsius; <, less than]

Local well number	USGS well number	Date	Well depth (feet)	Specific conductance (µS/cm)	pH (units)	Oxygen, dissolved (mg/L)	Nitrogen (mg/L) Nitrate	Nitrogen (mg/L) Nitrite	Nitrogen (mg/L) Ammonia	Nitrogen (mg/L) Organic	Phosphorus (mg/L) Dissolved ortho	Phosphorus (mg/L) Dissolved,
Coarse-grained upland sediments adjacent to a nontidal creek (Walls Landing Creek)[2]—Continued												
WLC00a	63F87	08-23-93	3.9	568	7.38	0.02	2.0	0.35	0.02	<0.2	0.01	0.02
WLC00b	63F88	08-23-93	7.4	615	7.49	1.0	6.0	.06	.03	.2	<.01	.01
WLC00c	63F89	08-23-93	8.8	609	7.62	.7	4.5	.12	.02	<.2	<.01	.01
WLC00d	63F90	08-23-93	14.9	610	7.70	.9	<.05	<.01	.04	<.2	.01	.04
WLC00e	63F91	08-23-93	18.2	600	7.68	.02	.091	<.01	.06	<.2	.02	.03
W.L. Creek[3]	--	08-23-93	--	440	5.3	5.3	3.8	<.01	.03	.3	.01	.02

[1]This is a surface-water sample from Cherrystone Inlet adjacent to well cluster CSW00.

[2]This transect also includes well cluster WLC300 in "Coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh."

[3]This is a surface-water sample from Walls Landing Creek adjacent to well cluster WLC00.

Concentrations of phosphorus and most forms of nitrogen tended to be low. Concentrations of dissolved phosphorus, orthophosphorus, nitrite, and organic nitrogen were near, or less than, detectable concentrations (table 3). The concentration of ammonia was detected in water from all wells, but was less than 0.2 mg/L as N in water from most wells. The concentration of nitrate was less than the detection limit (0.05 mg/L as N) in water from wells LC50a, LC50e, LC51a, and LC100e, where the concentration of dissolved oxygen was near 0.0 mg/L (fig. 12). The nitrate concentration ranged from 9.9 to 14 mg/L as N where the concentration of dissolved oxygen was the greatest in the shallowest two wells at clusters LC00 and LC10.

The nitrate concentration in the ground water was clearly affected by the combined effects of agricultural practices and the organic content of the sediment. Even directly beneath the water table that underlies the agricultural field (cluster LC50 and well LC51a), nitrate was less than the detectable concentration. The concentration of nitrate was only elevated in water from shallow wells near the creek where sediments beneath the field are coarse-grained and contain little organic material. The concentration of 11 mg/L as N in water from well LC00a, open near the water table, is similar to the concentration in other shallow wells at clusters LC00 and LC10; thus, the approximately 100-ft-wide riparian woodland between the field and cluster LC00 appears to have little effect on the concentration of nitrate in ground water that flows beneath it.

Although the effects of variations in the dissolved-oxygen concentration are evident in the nitrate concentration, the fate of the nitrogen is uncertain; ammonium that is applied as excess fertilizer either can nitrify to nitrate then denitrify to nitrogen gas or can be retained in the soils by cation exchange. If nitrification is followed by denitrification, then nitrogen gas would be produced and could be detected at concentrations exceeding concentrations contributed by the atmosphere based on the concentration of argon gas. Nitrogen gas in water from wells LC00c, LC00d, LC10d, and LC50a were only slightly in excess (1.2 to 3.6 mg/L) of concentrations that correlate to atmospheric contributions based on the concentration of argon gas when water recharges at 14°C (table 4). This temperature is the approximate recharge temperature reported for ground water on the southern end of the Eastern Shore (Dunkle and others, 1993). The excess nitrogen gas in water from well LC50a is about one-third of the amount of nitrate nitrogen present in the oxygen-rich water. Denitrification may take place, but the concentration of nitrogen gas does not account for all of the nitrogen that would result from denitrification (9.9 to 14 mg/L

Table 4. Concentrations of dissolved gases in water from selected wells along transects in different geohydrologic environments on the Eastern Shore, Virginia

[mg/L, milligrams per liter; °C, degrees Celsius; --, no data]

Local well number	Date	Well depth (feet)	Methane (mg/L)	Carbon dioxide (mg/L)	Dissolved oxygen (mg/L)	Argon (mg/L)	Nitrogen (mg/L)	Nitrogen[1] at 15°C recharge (mg/L)	Excess nitrogen (mg/L)
Fine-grained upland sediments adjacent to an estuary (Leatherberry Creek)									
LC50a	08-17-93	7.5	0.140	53.9	0.39	0.641	20.6	17.0	3.6
LC10d	08-16-93	21.1	.000	26.2	.67	.705	22.0	20.8	1.2
LC00c	08-17-93	13.1	.000	28.5	1.21	.709	22.3	21.0	1.3
LC00d	08-17-93	19.3	.115	20.6	.06	.717	23.0	21.5	1.5
Coarse-grained upland sediments adjacent to an estuary (Cherrystone Inlet)									
CSF50d	08-10-93	22.0	.000	68.7	.4	.707	27.7	20.9	6.8
CSF25e	08-11-93	22.6	.000	56.7	.04	.695	21.4	20.2	1.2
CSW10b	08-11-93	10.4	.000	62.0	.06	.694	24.9	20.1	4.8
CSW00c	08-12-93	16.6	.000	85.8	.05	.682	21.8	19.4	2.4
Coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh (Magothy Bay)									
WDM30e	08-05-93	19.2	.000	1.33	.01	.686	24.5	19.7	4.8
WDM40c	08-04-93	10.0	.000	15.2	.30	.669	26.3	18.6	7.7
WDM50b	08-04-93	5.6	.000	176	.04	.664	19.4	18.3	1.1
WDM75c	08-03-93	9.0	.000	26.5	.05	.668	19.7	18.6	1.1
Coarse-grained upland sediments adjacent to a nontidal creek (Walls Landing Creek)									
WLC50a[2]	08-18-93	3.6	1.69	119	.02	.572	17.8	--	--
WLC00a[2]	08-23-93	3.9	.000	3.9	.02	.576	20.8	--	--
WLC00e	08-23-93	18.2	.000	2.6	.02	.681	30.8	19.4	11.4

[1]Concentration of nitrogen gas in solution was based on the argon gas concentration in solution if the ground water was in equilibrium with the atmosphere, even if under pressure, when recharged at 14°C.

[2]Sample appears to be contaminated or otherwise of questionable accuracy.

as N of nitrate); thus, cation exchange also appears to be a significant process. Ammonia retained in the soils by cation exchange can remain available for plant uptake.

Implications of the Geohydrology and Geochemistry on Land-Use Management Practices

The Leatherberry Creek site shows the effects of a variety of geohydrologic and geochemical processes present in areas underlain by fine-grained sediments with important implications for land-use management practices designed for water-quality protection. From a geohydrologic standpoint, the fine-grained sediments and low topographic relief cause poor natural drainage (particularly through the ground-water system) and low rates of ground-water recharge. The presence of agricultural fields and residential development primarily near the tidal creeks and the presence of woodlands in the interiors of these peninsulas, in part, reflect the response of the current land use to this poor drainage. Topographic maps show interior areas having extensive local ditching but little clearing of the land; thus, draining interior areas for uses other than woodland uses appear to be difficult.

Evapotranspiration appears to be a major discharge pathway from the shallow ground-water system. Clearing the trees from the interior areas for other land uses will reduce evapotranspiration as a pathway for discharge of water and would probably result in a shallow water table and standing water for longer periods and over a greater area than under current conditions. Artificially improving the drainage from the interior areas for development will discharge water through surficial pathways that would otherwise discharge by ground-water flow and evapotranspiration; although, the amount of water that discharges through ground-water pathways to the tidal creeks and estuaries under current conditions appears to be small. Such changes can alter the pathways and the loads of contaminants that discharge to the tidal creek and estuaries.

From a geochemical standpoint, the fine-grained sediment that contains abundant organic material typically present in this area can cause a low concentration of dissolved oxygen in ground water. In these low-oxygen environments, nitrification of ammonium to nitrate is inhibited, and denitrification of nitrate to nitrogen gas likely will occur. The contribution of nitrogen from the ground water to tidal creeks and estuaries and other surface-water bodies would be small and, therefore, would limit the eutrophication of surface-water bodies by nitrogen from ground-water sources. These conditions can be an important mechanism for limiting ammonium and nitrate discharge from land uses that naturally contribute large loads of ammonium and nitrate, even where the ground water flows along short and shallow flow paths. These geohydrologic and geochemical conditions would reduce the loads of nitrogen from agricultural and residential application of fertilizer that would be transported through ground water to the estuaries. These conditions also can result in the rapid denitrification of nitrate-based fertilizers when they are applied, thereby, reducing the nitrogen available to plants and increasing the rate of application needed for the desired growth. Organic-nitrogen and ammonia-nitrogen fertilizers would more likely remain available for plants, thereby reducing the amount of fertilizer required for desired growth. Although these areas can reduce nitrogen loads from septic tanks, maintaining significant residential development with properly operating septic tanks can be difficult because of the poor drainage. The fine-grained sediments that contain abundant organic material of this ground-water systems can naturally limit loads of ground-water contaminants that discharge to the surface because of the low rates of ground water recharge and flow.

The presence of local coarse-grained sediments that contain little organic material also is geohydrologically and geochemically important. The local coarse-grained sediments provide better drainage and greater recharge rates. Much of the residential and agricultural development on the peninsula is near the tidal creeks and estuaries, where the coarse-grained sediments were identified at the study site. Effects of land use in areas with local coarse-grained sediments that contain little organic material will be similar to those in similar regional geochemical systems; the concentration of nitrate from fertilizers, septic tanks, and other sources can be significant in ground water beneath such areas. Adjustment of the rate and timing of fertilizer application and the type of fertilizer applied can reduce loads of nitrate transported through the ground water from the fields to the estuaries. If the time of application is changed, but the crop needs and the annual rate of application are unchanged (rates remain based on applications rates for the previous timing that met crop needs when nitrate leached from the soils at high rates), then residual nitrate will remain in the soils and will likely leach into the ground water at rates similar to those before the change in timing. As residential development continues to increase, loads of nitrate from septic tanks will increase. Limits on the residential density will limit loads of nitrate contributed by septic tanks through the ground water to the estuaries.

This site also shows that the composition of underlying sediments can have a greater role than riparian woodlands in the transport and geochemical processing of nitrogen through the saturated zone. Riparian woodlands appeared to have minimal effect on the removal of nitrate nitrogen from the ground water; although, riparian woodlands can significantly improve the quality of surface runoff by removing sediment and nutrients. Thus, preserving riparian woodlands remains an important management technique for protecting the quality of creeks and estuaries from the effects of surface runoff, although the effects of riparian woodlands on ground-water quality may be limited. The significance of the contrasting geochemical processes in oxygen-rich and low-oxygen environments and the role of riparian woodlands will be further discussed for the other study sites.

Ground Water Discharging from Coarse-Grained Upland Sediments to an Estuary (Cherrystone Inlet)

Local geohydrologic and geochemical processes at the Cherrystone Inlet site again controlled the transport of nitrate to the estuary. Although this site was selected to represent an environment in which geohydrologic and geochemical processes provide little protection from the discharge of ground water containing abundant nitrate, the local presence of fine-grained, sediments that contain abundant organic material and an overlying woodland at this site significantly affected the ground-water flow and geochemistry.

Geohydrology

Ground-water primarily flows along local pathways at the Cherrystone Inlet site, with horizontal hydraulic gradients and ground-water flow from the center of the local peninsula to the creeks and inlet. Little, if any, ground water flows through the surficial aquifer from the center of the main Eastern Shore peninsula to the creeks and inlet because of the relatively flat land surface and low hydraulic gradient from the central uplands. Because the high permeability of the coarse-grained sediment allows precipitation to rapidly infiltrate into and flow through the surficial aquifer, drainage does not appear to be a problem in the fields even though natural surface drainage is poorly developed and few small ditches have been dug to drain the fields.

Ground-water levels at this site reflected seasonal changes in recharge to, and discharge from, the ground-water system that are typical of the Eastern Shore (fig. 13). Ground-water levels in wells at cluster CSF50 in the center of the peninsula ranged from about 5.5 ft above sea level during the winter to less than 2 ft above sea level during the summer. At cluster CSF25 at the top of the bluff between the field and the estuary, water levels remained less than 1 ft above sea level throughout the year decreasing from about 0.95 ft above sea level during the winter to about 0.4 ft above sea level during the summer. Although cluster CSW00 is closer to the estuary and at a lower land-surface altitude than cluster CSF25, water levels at CSW00 generally were at a higher altitude than at CSF25, particularly during the winter recharge period, ranging from about 1.8 ft above sea level during the late winter to about 0.5 ft above sea level during the late summer. Therefore, ground water probably flowed farther beneath the estuary and discharged at a slower rate and over a larger bottom area of the estuary where the permeability of the sediments is low than where the permeability is high.

Horizontal hydraulic gradients ranged from 0.00040 to 0.0056 and generally were toward the estuary (fig. 14). These horizontal gradients were less

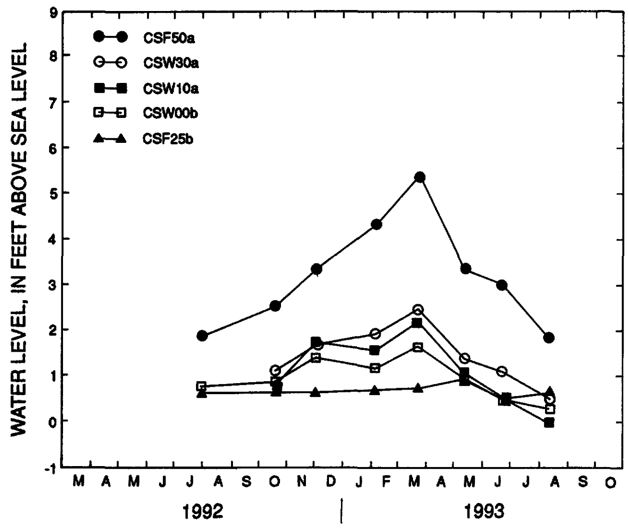


Figure 13. Water levels in selected wells at the site with coarse-grained upland sediments adjacent to an estuary, Eastern Shore, Virginia.

than the horizontal gradients at the Leatherberry Creek site, because less head is lost as ground water flows through coarse-grained, permeable sediment than when water flows through fine-grained, less permeable sediment. Horizontal gradients in the water table were landward between clusters CSW00 and CSW10 in October 1992 and August 1993 but remained seaward within the underlying coarse-grained sediments. Vertical gradients at clusters CSW00 and CSW10 varied, ranging from downward 0.0018 to upward 0.0257 and downward 0.0146 to upward 0.0269, respectively. Vertical gradients were upward at clusters CSW10 throughout the warm-weather months when evapotranspiration rates were high and downward or negligible during cold-weather months (figs. 14 and 15). The seasonality in the vertical gradients indicates that the upward gradient results from the effects of evapotranspiration through the overlying riparian woodland on ground-water levels. Evapotranspiration from the woodland also can account for the landward gradient between clusters CSW00 and CSW10; thus, evapotranspiration to the woodland can be an important ground-water-discharge pathway. The predominantly upward gradient at CSW00 probably reflects the combined effects of evapotranspiration and the upward leakage of water through the fine-grained sediments as ground water flowed toward, and discharged to, the estuary. Vertical gradients at cluster CSW30 were small and generally within the accuracy of the measurement method.

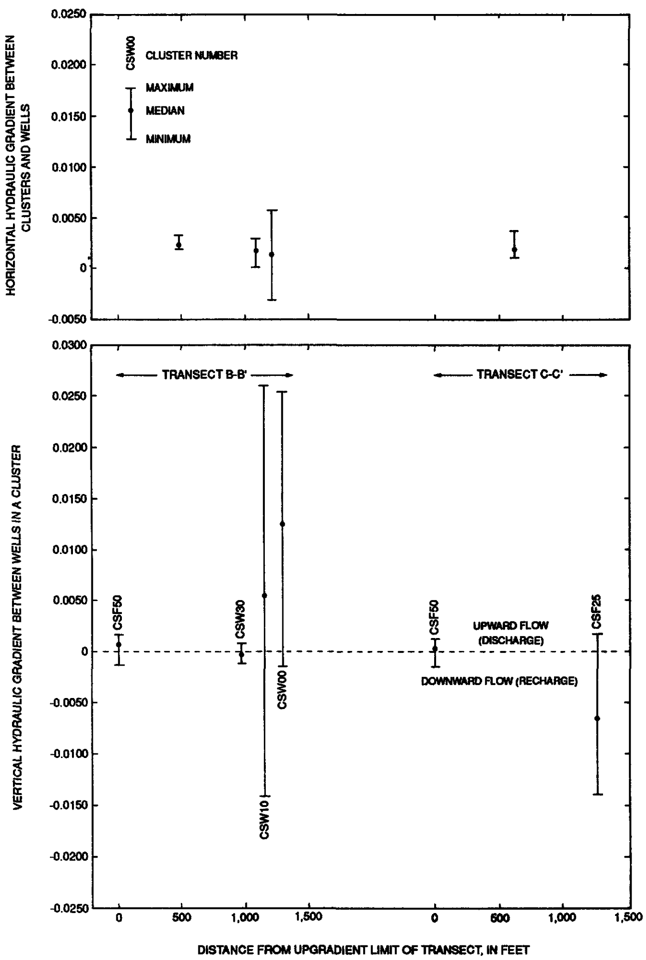


Figure 14. Horizontal and vertical hydraulic gradients at the site with coarse-grained upland sediments adjacent to an estuary, Eastern Shore, Virginia. (Negative vertical gradients are downward and positive vertical gradients are upward.)

Vertical hydraulic gradients generally were downward at cluster CSF25, ranging from downward 0.0140 to upward 0.0016 (fig. 14), indicating the cluster usually is in the recharge area. The vertical gradients at cluster CSF25 were upward in February and March 1993 when water levels and horizontal hydraulic gradients throughout the site were greatest. Although cluster CSF50 was located at the center of the peninsula and the recharge area, vertical hydraulic gradients were always within the measurement error. The reason for the small vertical hydraulic gradient is unclear but can result from the little head loss that would result when water flowed through the sediments of high permeability.

The age of the ground water ranged from less than 1 year from well CSW30b to 26.0 years from well CSW30d (table 1 and fig. 16). The depth to which the recently recharged water extended was greater at this site (fig. 16) than at the Leatherberry Creek site (fig. 10). Younger water was apparently overlain by older water at clusters CSF50 and CSW30. However, the differences in age in the upper three wells at cluster CSF50 were within the accuracy of the measurement. Young water extends deeper at this cluster than at the previously discussed site, indicating higher recharge rates and high sediment permeability. Estimates of recharge rates are not presented for this site because the accuracy of such values is questionable; ages at cluster CSF50 with older water over younger water make calculations of recharge rates unreliable, and the only other cluster at which vertical hydraulic gradients indicate a recharge area is CSF25 at the edge of the estuary. A large part of the flow at cluster CSF25 probably is horizontal, which introduces errors in recharge estimates by use of age.

The presence of salty water in the surficial aquifer, as indicated by specific conductance (table 5), appears to be controlled by water levels and local variability in the flow system at the site. At cluster CSF50, specific conductance of the water generally

Table 5. Specific conductance of water from zone testing at the time of well installation at the site with coarse-grained upland sediments adjacent to an estuary (Cherrystone Inlet), Eastern Shore, Virginia

[µS/cm microsiemens per centimeter at 25°Celsius]

Date	Depth below land surface (feet)	Specific conductance (µS/cm)
	Cluster CSF00	
07-22-95	5.1	17,340
07-22-95	7.1	16,050
07-22-95	10.9	10,100
07-22-95	12.5	3,800
07-22-95	15.1	3,800
07-23-95	16.4	3,400
07-23-95	19.3	3,990
07-23-95	21.1	3,640
07-23-95	23.4	3,500
	Cluster CSF25	
07-28-92	10.4	292
07-28-92	11.8	527
07-28-92	14.4	670
07-28-92	17.1	1,768
07-28-92	18.4	2,120
07-28-92	20.0	8,900
07-28-92	22.8	13,200

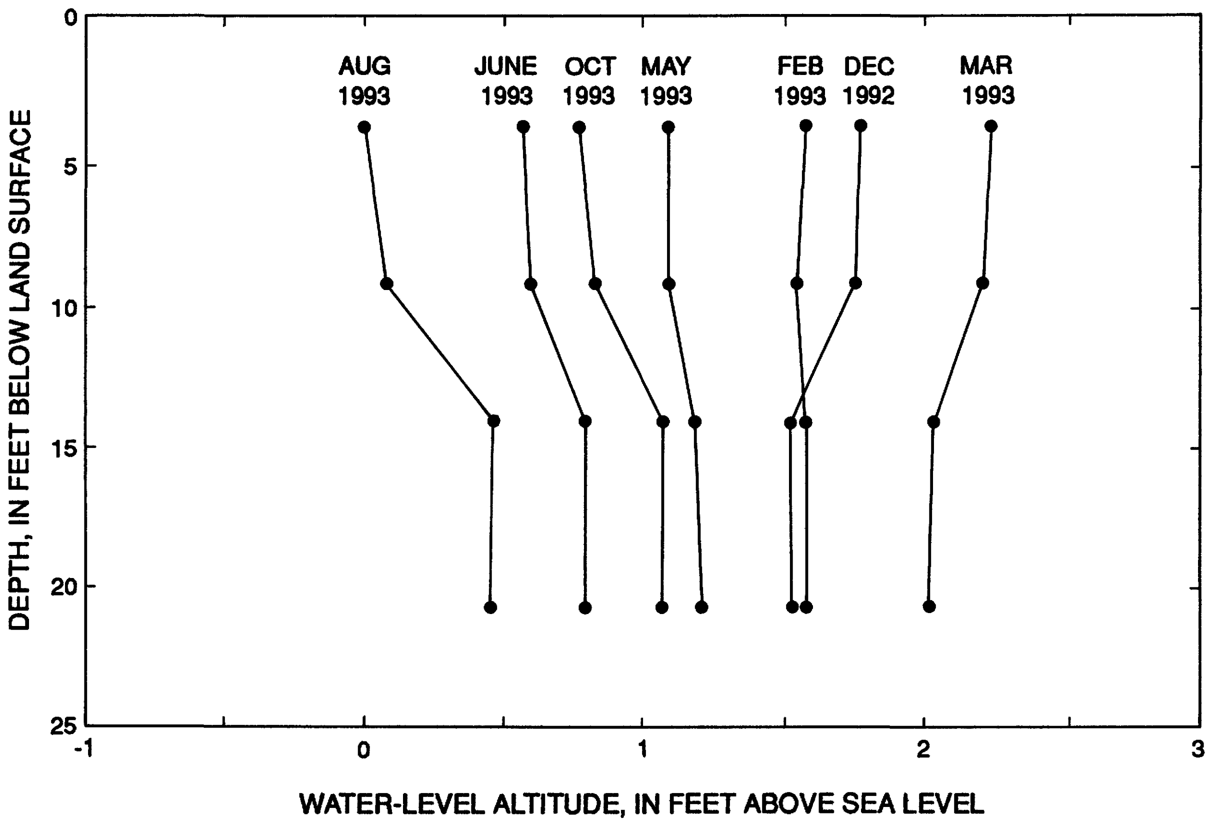
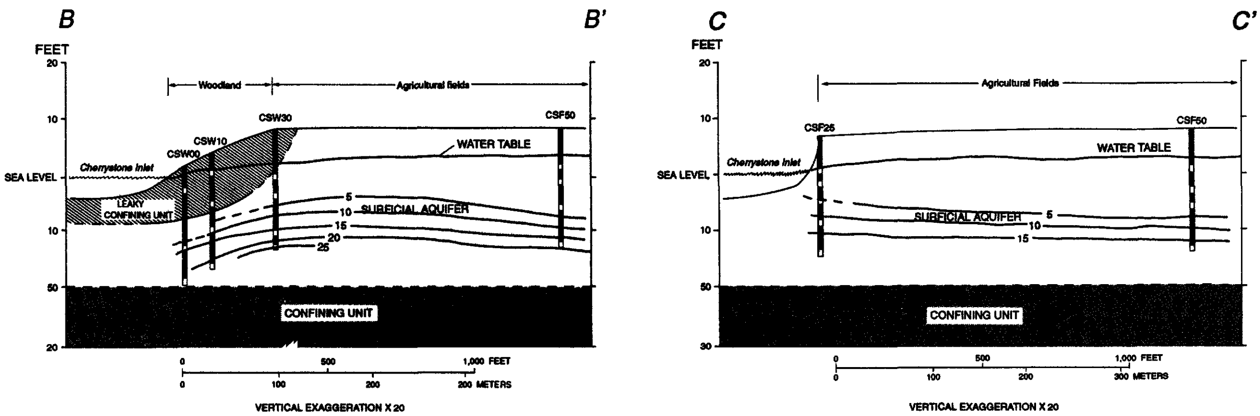


Figure 15. Vertical distribution in head at cluster CSW10 at the site with coarse-grained upland sediments adjacent to an estuary, Eastern Shore, Virginia.

increased with depth from 370 µS/cm at the water table to 703 µS/cm in the deepest well (table 3 and fig. 17). Cluster CSF25 was the only cluster at which specific conductance approached that of the estuary (about 29,000 µS/cm) in the deepest well during the study (table 5). When the deepest well at this cluster was driven during a period of low ground-water levels, specific conductance increased from 292 µS/cm at the water table to 13,200 µS/cm at 22.8 ft below land surface (15 ft below sea level). The calculated depth to the saltwater interface, based on the Ghyben-Herzberg relation for seawater and the altitude of the water table of 0.52 ft above sea level at that time, was 20 ft below sea level. Although the density of the water in Cherrystone Inlet is less than that of seawater, the relation predicts that saltwater would be approached at the depth of the deepest well. Because the water levels in that well increased during the year, the specific conductance of water from the deepest well decreased to about 700 µS/cm, similar to that of water at an equivalent altitude at cluster CSF50 in the center of the peninsula.

The distribution of salty water also was affected by the presence of local deposits of fine-grained sediments that form the leaky confining unit. The low permeability of the shallow sediments does not permit salty water to readily flush from the sediments. Based on discussions with individuals familiar with the area, land surface inland of cluster CSW10 is inundated by saltwater during unusually high tides. This saltwater recharges the shallow part of the leaky confining unit and only slowly flushes from it. The specific conductance of water from wells in the fine-grained sediments at clusters CSW00 and CSW10 was greater than that of the deeper, coarse-grained sediments (fig. 17). A sharp decrease in specific conductance was observed when wells were driven into the underlying more permeable sediments at these clusters. The specific conductance when the wells were installed was 17,340 µS/cm at the top of the water table at cluster CSW00 and gradually decreased to 10,100 µS/cm at the bottom of the fine-grained sediments (10.9 ft beneath land surface) (table 5). The specific conductance sharply decreased beneath the fine-grained sediments



EXPLANATION

—10-- LINE OF EQUAL MODELED AGE--Dashed where approximately located. Interval, in years since recharged at the water table, is 5

WELL CLUSTER

CSF25 Number

Cased part of wells

2.6-foot-long screened interval--Each screened interval is for a separate well in the cluster

Figure 16. Geohydrologic section showing ground-water age calculated from chlorofluorocarbon concentration at the site with coarse-grained upland sediments adjacent to an estuary, Eastern Shore, Virginia. (Location of lines of section shown on figure 6.)

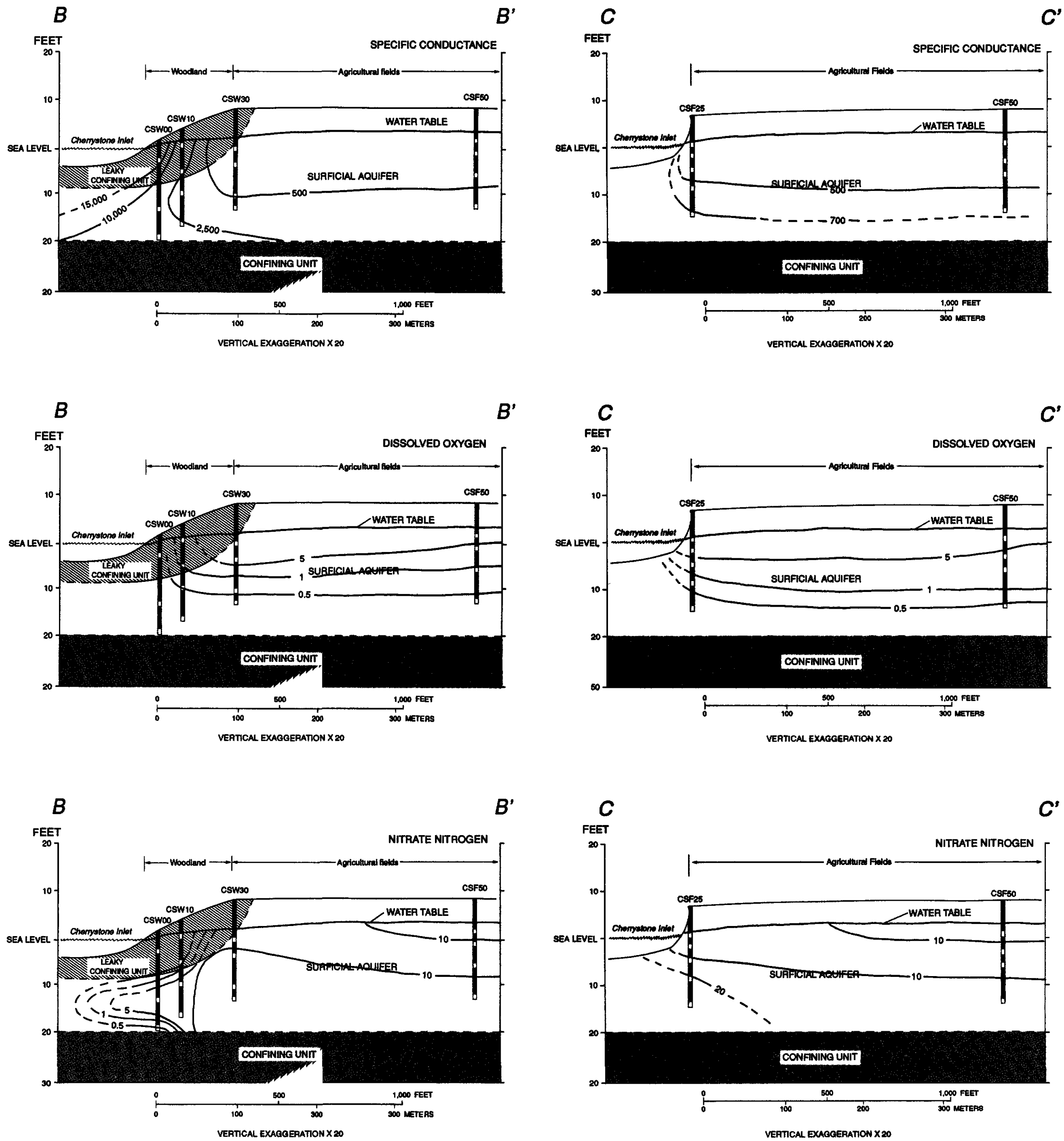
to 3,800 µS/cm in the underlying coarse-grained sediments. Specific conductance was lower at cluster CSW10 although the relative distribution was similar. The decrease in specific conductance with depth also indicates dilution of salty water with freshwater that discharges upward from the coarse-grained aquifer sediments to the fine-grained sediments of the leaky confining unit as a result of evapotranspiration.

Geochemistry

Concentrations of most major ions increased with depth in water from wells at clusters CSF25, CSF50, and CSW30, but decreased with depth at cluster CSW10 (table 2). Ground water can be grouped into two major categories based on the dominant ions: (1) ground water that is dominated by dilute saltwater; (2) ground water that has little effect of saltwater (fig. 18). Wells that contain water affected by dilute saltwater are those open to or beneath the fine-grained sediments at clusters CSW00 and CSW10. Sodium and chloride ions dominate the quality of water from these wells. Water from wells at the other cluster had a similar quality that differed from that at clusters CSW00 and CSW10: calcium and magnesium were the dominant cations, and sulfate was the dominant anion. Sulfate is commonly elevated in ground water on the Eastern Shore of Virginia (Hamilton and others, 1993). These differences in water quality further emphasize the effects of the surficial fine-grained sediments on ground-water flow.

The concentration of dissolved oxygen ranged from 5.4 to 8.0 mg/L in water from wells nearest the water table and decreased with depth to 0.5 mg/L, or less, below a depth of about 20 ft at the clusters in the coarse-grained sediments (fig. 17). The concentration of dissolved oxygen usually was 1.0 mg/L, or less, in water from all wells at clusters CSW00 and CSW10. The concentration of dissolved oxygen was 1.0 mg/L, or less, in water that was in the aquifer for more than 8 years except for 1.4 mg/L in water from well CSW30c.

Figure 17. Geohydrologic section showing specific conductance and concentrations of dissolved oxygen and nitrate in ground water at the site with coarse-grained upland sediments adjacent to an estuary, Eastern Shore, Virginia. (Location of lines of section shown on figure 6.) ▶



EXPLANATION

—10-- LINE OF EQUAL VALUE OF INDICATED VARIABLE--Dashed where approximately located. Interval is variable. Specific conductance is in microsiemens per centimeter at 25°C, dissolved oxygen is in milligrams per liter, and nitrate nitrogen is in milligrams per liter as nitrogen

WELL CLUSTER

CSF25 Number

Cased part of wells

2.6-foot-long screened interval--Each screened interval is for a separate well in the cluster

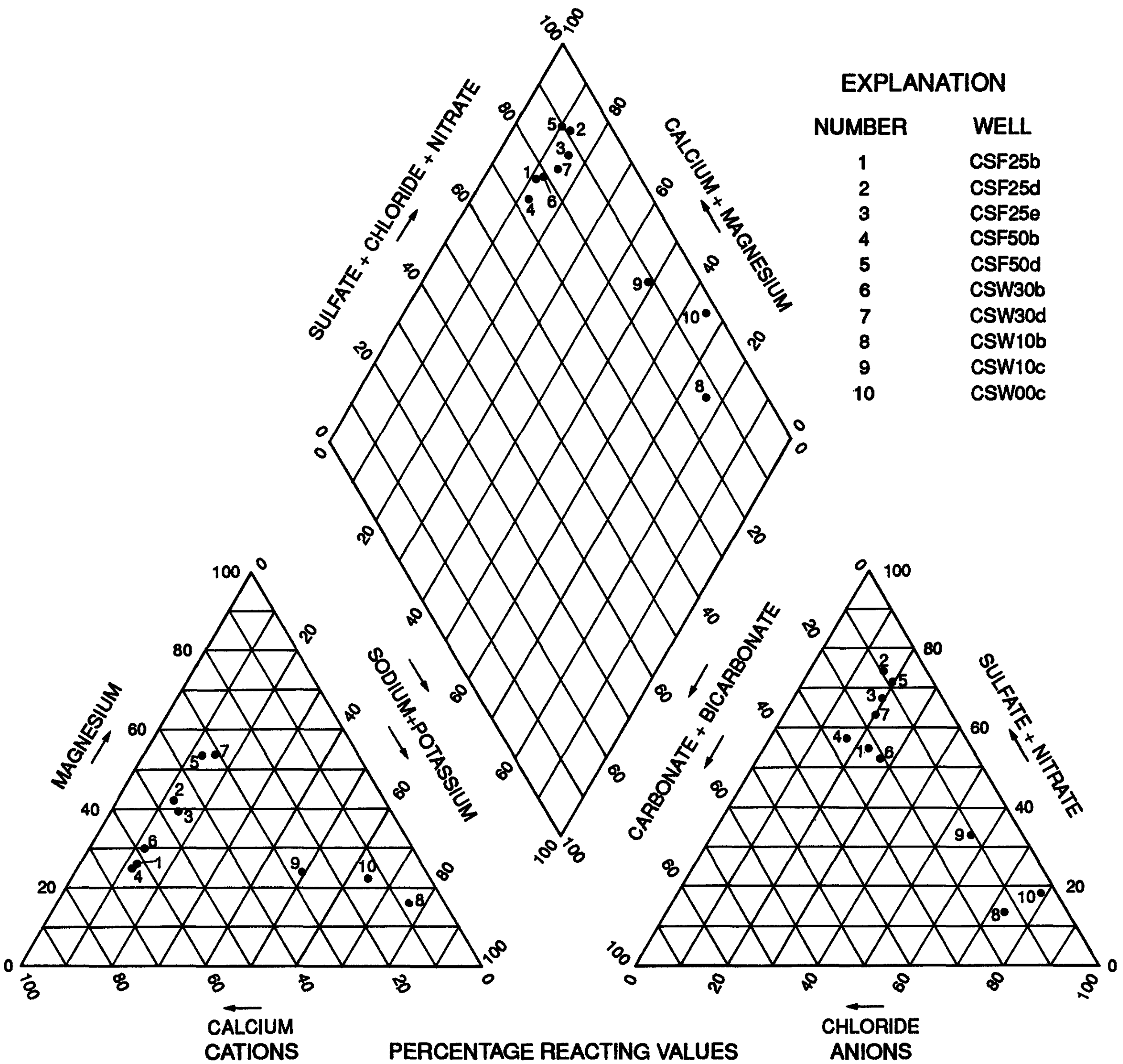


Figure 18. Relative ionic composition of ground water at the site with coarse-grained upland sediments adjacent to an estuary, Eastern Shore, Virginia.

Dissolved phosphorus and orthophosphorus concentrations were at, or less than, detectable concentrations in water samples from all wells (table 3). Concentrations of nitrite and ammonia were near, or less than, detectable concentrations in water having a concentration of dissolved oxygen exceeding 1.5 mg/L but were as much as 0.90 and 0.23 mg/L as N, respectively, in water having a low dissolved oxygen concentration. Concentrations of nitrite and ammonia, however, were small compared to the concentration of nitrate in the oxygen-rich ground water.

The concentration of nitrate nitrogen ranged from 0.13 to 27 mg/L as N (table 3 and fig. 17). Although denitrification can decrease the nitrate concentration as the dissolved oxygen concentration approached 0 mg/L, the nitrate concentration remained high in parts of the aquifer having low dissolved oxygen concentration. The three greatest concentrations of nitrate were in water having a concentration of dissolved oxygen 0.7 mg /L or less; this water also among the water that had been in the aquifer for the longest period. Of the seven samples in the aquifer less than 10 years, the concentration of nitrate nitrogen ranged from 7.7 to 15 mg/L as N, with a median of 9.0 mg/L as N. Of the seven samples of water in the aquifer more than 10 years, the concentration of nitrate nitrogen ranged from 8.0 to 27 mg/L as N with a median of 14 mg/L as N; therefore, recent agricultural practices used at this site appear to leach less nitrate into the ground water than older practices. The elevated concentration of nitrate in water at cluster CSF25 can be easily transported by the ground-water discharge to the estuary. Geochemical processes, primarily denitrification, near the sediment-water interface probably are the primary processes by which the load of nitrate in water discharged along this pathway can be decreased.

The elevated concentration of nitrate also was transported through the coarse-grained aquifer beneath the several hundred feet of riparian woodland. The lowest nitrate concentration (0.39 mg/L as N) was observed in the deepest well at cluster CSW00; the concentration in the other three wells in these sediments was 8.0 to 9.0 mg/L as N. The concentration of nitrate nitrogen in both wells (CSW00b and CSW10b) open to the fine-grained sediments was 0.13 mg/L as N; the concentration of dissolved oxygen in these wells was less than 0.5 mg/L. Dissolved oxygen in water from these wells was probably low as a result of the sluggish flow in, and greater organic content of, the fine-grained sediments. Using dilution estimates base on concentrations of chloride and nitrate in water from wells CSW10b and CSW10c, the low concentration of nitrate in the fine-grained sediments appears to result primarily from dilution with salty water having a low concentration of nitrate in which little denitrification has occurred. Denitrification likely results from the organic material deposited with the sediments, not the presence of riparian woodland because of the upward flow regime. The occurrence of denitrification also is supported by the greater amount of excess nitrogen gas in water from well CSW10b (24.9 mg/L of nitrogen gas) than from well CSW10c (21.8 mg/L of nitrogen gas) (table 4). Excess nitrogen gas (4.8 mg/L) in water from well CSW10b would account for less than half of the nitrate commonly present in ground water at this site.

Little ground water from the fine-grained sediments beneath the woodland probably discharges to the estuary because of the slow rates of horizontal flow through fine-grained sediments and the discharge of ground water by evapotranspiration through the woodland indicated by the seasonal changes in the vertical hydraulic gradient (fig. 15). The rates of horizontal flow through the fine-grained sediments were probably low because the vertical hydraulic gradients can be more than eight times the horizontal gradient (fig. 14); although, a contrast in the horizontal and vertical hydraulic conductivity of the sediments can contribute to differences in horizontal and vertical hydraulic gradients. Little ground water in the fine-grained sediments beneath the woodland may discharge to the estuary, but ground water in the underlying coarse-grained sediment probably flows beneath the woodland and discharges over a large area through the fine-grained sediments to the estuary. Denitrification probably reduces the concentration of nitrate in ground water that discharges through these sediments as indicated by the low concentration of nitrate in water from wells in the fine-grained sediments beneath the woodland; however, the magnitude of such effects is unknown. The geohydrologic and geochemical processes that affect the concentration and load of nitrate discharging with ground water through the fine-grained sediments to the estuary result from the sediment permeability and organic content, not the current presence of a riparian woodland. Thus, the riparian woodland appears to have little effect on concentration of nitrate nitrogen but can affect load by uptake through evapotranspiration.

Implications of the Geohydrology and Geochemistry on Land-Use Management Practices

The geohydrologic and geochemical processes identified at the Cherrystone Inlet site have important implications when evaluating land-use management practices where ground water flows from coarse-grained, upland sediments directly to an estuary or through fine-grained sediments to an estuary. The site shows how these processes can be distributed where fine-grained sediments were deposited beneath and adjacent to the estuary and were locally eroded from parts of the shore or were not deposited. The presence of the fine-grained sediments around Cherrystone Inlet appear to be indicated by the gradual slope in land surface toward the estuary, soils, and the presence of woodlands and marshes. Coarse-grained sediments adjacent to the estuary appear to be present as indicated by more abrupt changes in land-surface altitude adjacent to the estuary. The flow inhibiting characteristics of the fine-grained sediments can affect the spatial distribution of ground-water discharge beneath the estuary. Ground water probably discharges over a greater area and at a slower rate per unit of bottom area through fine-grained sediments than through coarse-grained sediments. This provides greater opportunity for geochemical processes to change the concentration of nitrate in ground-water discharge. In areas where coarse-grained sediments are continuous from upland fields to the estuary bottom, ground water can discharge readily to the estuary, providing a direct transport pathway for nitrate. These relations are consistent with other work around Cherrystone Inlet by Reay and others (1993) in which the rate of ground-water discharge to the estuary per unit of bottom area was about 10 times greater through coarse-grained bottom sediments than through fine-grained bottom sediments.

Differences in ground-water flow are accompanied by differences in geochemical processes. Nitrate in ground water discharged through coarse-grained sediments that contain little organic material will be little affected by geochemical processes except in local environments where abundant organic material promotes denitrification. Such environments can include sediments at the sediment-water interface where organic material was recently deposited at the bottom of the estuary. Investigation of these environments was beyond the scope of this study.

Organic material that is commonly present in the fine-grained sediments will promote denitrification and decrease loads of nitrate as ground water flows through these sediments and discharges to the estuary. This provides a natural mechanism for decreasing loads of nitrate in ground water that discharges to the estuary. Although the coarse-grained sediments that underlie the fine-grained sediments provide a transport pathway for water with an elevated concentration of nitrate to flow beneath the riparian woodland and the estuary, denitrification as the ground water flows vertically through the fine-grained sediments that contain abundant organic material can provide natural protection of the quality of estuarine water from the effects of ground-water discharge.

Based on ground-water-flow paths and other evidence, the riparian woodland at this site does not appear to have the major role in the decrease in the concentration of nitrate in ground water that flowed beneath it. Although the natural sediment composition rather than the riparian woodlands probably provides the organic material for denitrification of nitrate in ground water, the woodlands can reduce the load of nitrate discharging to the estuary by the uptake of ground water by evapotranspiration and the incorporation of dissolved nitrate in plant tissue. The amount of water and nitrate removed by this pathway at this site is not known. However, the bulk of the ground water probably flows beneath the woodland and discharges to the estuary. The amount of ground water discharged through evapotranspiration by riparian woodlands depends on the width of the riparian woodland, the depth of the water table, and other geohydrologic conditions.

The location of land-use practices in upland areas underlain by coarse-grained sediments can affect the amount of nitrate that discharges through the ground water to an estuary differently depending on the ground-water-flow path and the geochemical processes along each flow path. Although it is difficult to draw specific conclusions about the effects of particular land-use management practices on the concentration of nitrate in ground water, preliminary observations at a site of various types of information, such as grain size and the apparent organic content of sediments, can help minimize loads of nitrate discharged to an estuary. As at the Leatherberry Creek site where coarse-grained sediments are adjacent to the estuary, adjustment of the rate and timing of fertilizer application and the type of fertilizer applied can reduce loads of nitrate transported through the ground water from the fields to the estuaries. In areas with residential development, limits on the density of residences will limit loads of nitrate contributed by septic tanks through the ground water to the estuaries. Where the fine-grained sediments and riparian woodlands border the estuary, the timing of fertilizer application will not be as critical for reducing nitrate loads, and residential development can be more dense because denitrification and evapotranspiration reduce loads of nitrate discharged to an estuary. Where an estuary is bordered both by fine-grained and by coarse-grained sediments, local ground-water-flow paths need to be understood to differentiate recharge areas from which ground water discharges directly to the estuary from recharge areas where ground discharges through fine-grained sediments to riparian zones or an estuary.

Ground Water Discharging from Coarse-Grained Upland Sediments to a Wooded Wetland and Saltwater Marsh (Magothy Bay)

Broad lowlands, such as at the Magothy Bay site, potentially provide one of the greatest opportunities for reducing the ground-water load of nitrate discharged to an estuary because of low hydraulic gradients, uptake of water and dissolved nitrate by woodland plants, and denitrification in deep sediments of the surficial aquifer or the shallow wetland soils. The relative importance of these processes in reducing nitrogen loads depends on local geohydrology, geochemistry, and vegetation.

Geohydrology

Ground water in the surficial aquifer flows along a combination of regional and local flow paths at the Magothy Bay site. Ground water that is recharged toward the center of the peninsula and flows through the confined aquifers and through deep parts of the surficial aquifer flows along regional flow paths (fig. 4); ground water that remains in the shallow part of the surficial aquifer flows along local ground-water-flow paths and was recharged near, or in, discharge areas. Horizontal hydraulic gradients were from the central uplands of the Eastern Shore to the lowland wetlands (figs. 19 and 20). Median gradients increased from 0.0070 between clusters WLC300 and WDM00 to a maximum of 0.0176 between clusters WDM00 and WDM20. Median gradients decreased to relatively uniform values of 0.0030 between clusters WDM20 and WDM30, 0.0030 between clusters WDM30 and WDM40, and 0.0029 between clusters WDM40 and WDM50. Median gradients further decreased to 0.0005 between clusters WDM50 and WDM75. The horizontal hydraulic gradient decreased about 57 percent from the uplands (between clusters WLC300 and WDM00) to the first part of the woodland (between clusters WDM30 and WDM50) and decreased about 93 percent from the upland to between cluster WDM50 and WDM 75.

The decrease in horizontal hydraulic gradient was accompanied by a decrease in the saturated thickness of the surficial aquifer. The altitude of the water table decreased from about 18 to 5 ft above sea level between clusters WLC300 and WDM30 (fig. 20). The tops of the confining unit and the leaky confining unit that underlie the surficial aquifer rise

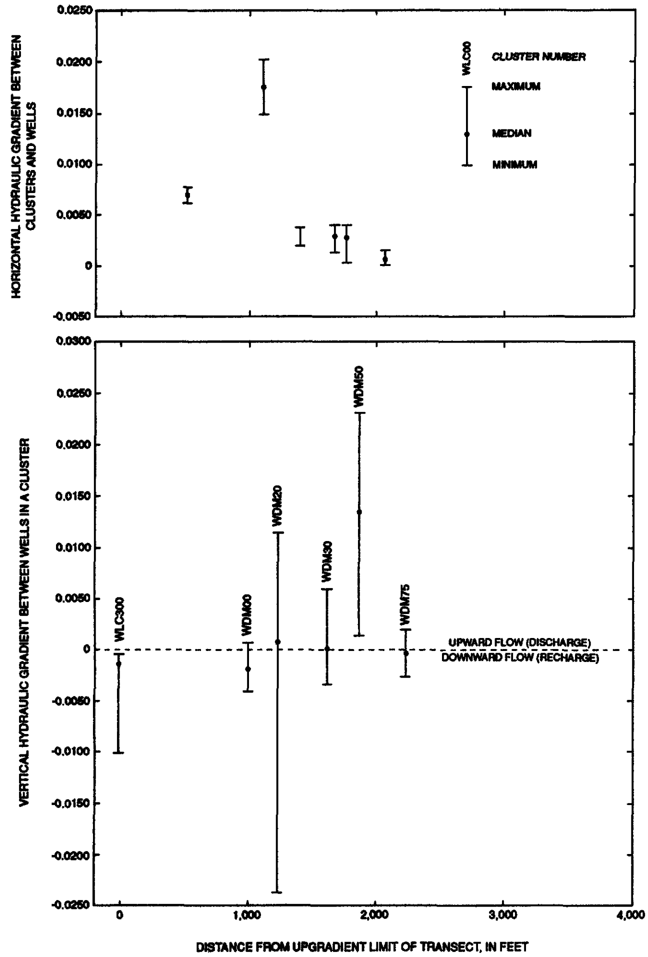
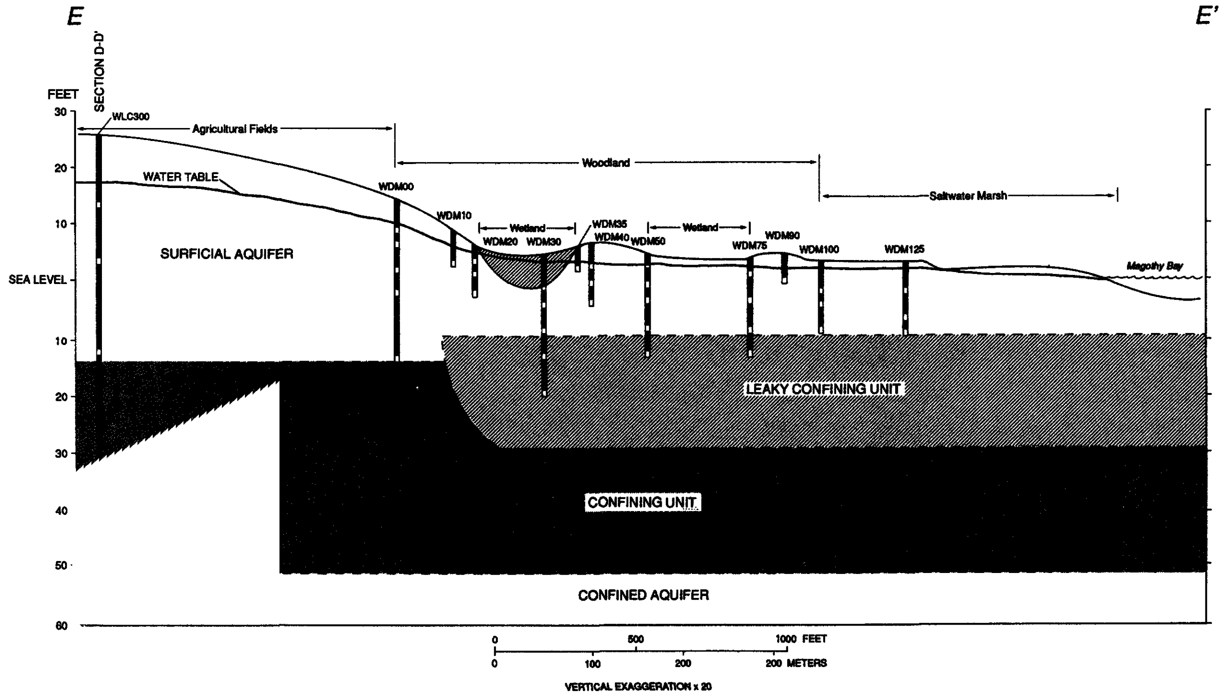


Figure 19. Horizontal and vertical hydraulic gradients at the site with coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh, Eastern Shore, Virginia. (Negative vertical gradients are downward and positive vertical gradients are upward.)

about 5 ft from about 14 to 9 ft below sea level between these same clusters. The combined effects of the decline in the altitude of the water table and rise in the altitude of the confining units decreased the saturated thickness from about 32 ft beneath the uplands (cluster WLC300) to about 15 ft beneath the wetland (cluster WDM30), a decrease of about 53 percent.

Based on Darcy's Law (Freeze and Cherry, 1979), the decrease in horizontal hydraulic gradient accompanied by the decrease in saturated thickness of the surficial aquifer indicates that the amount of ground water that flowed through the surficial aquifer beneath the woodland decreased, or the hydraulic conductivity of the aquifer increased, or both. If the



EXPLANATION

INDIVIDUAL WELL OR WELL CLUSTER

WDM30 **Number**

Cased part of wells

2.6-foot-long screened interval--Each screened interval is for a separate well in the cluster

Figure 20. Geohydrologic section showing lateral changes in the altitude of the water table and the top of the confining unit at the site with coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh, Eastern Shore, Virginia. (Location of line of section shown on figure 7.)

hydraulic conductivity of the aquifer increased and no ground water discharged to the surface, then the ground-water-flow velocities would have increased proportional to the combined decrease in saturated thickness of the surficial aquifer and horizontal hydraulic gradient. If no change in hydraulic conductivity accompanied the decrease in aquifer thickness and the decrease in hydraulic gradient, the ground-water-flow rates beneath the woodland would have decreased to less than 20 percent of the flow beneath the upland. Ground-water flow in the surficial aquifer beneath cluster WDM75 would have decreased to less than 5 percent of that at cluster WLC300 based on the decreased saturated thickness and horizontal gradient. The only way for the ground-water-flow rate to decrease would have been for the ground water to discharge from the surficial aquifer to the wetlands.

Vertical hydraulic gradients were consistently downward at cluster WLC300 and varied between upward and downward at cluster WDM00, but were predominantly downward (fig. 19). Thus, these clusters were in the ground-water-recharge area. Vertical gradients varied between downward and upward at clusters WDM20 and WDM30 but were more often upward indicating the tendency for ground water to discharge in these areas. The downward gradient may partly result from the constriction of ground-water flow by the peaty and clayey surficial deposits at cluster WDM30 that further decreased the saturated thickness of the aquifer. Vertical gradients were downward at cluster WDM40, possibly because the wells are in the upper part of the aquifer, and the cluster is located on a slight topographic high. Vertical gradients were predominantly upward at cluster WDM50, ranging from downward 0.0013 to upward 0.0235 (median upward 0.0134). The median vertical hydraulic gradient at cluster WDM50 was more than four times the median horizontal hydraulic gradient in this area. The magnitude of the upward gradient at WDM50 indicates that the cluster was in a ground-water-discharge area. The vertical gradient at cluster WDM75 varied between upward and downward but tended to be small, indicating little recharge or discharge of ground water at this cluster. On the basis of horizontal and vertical gradients, ground water discharges in the vicinity of clusters WDM30 and WDM50.

Ground-water levels fluctuated seasonally as a result of the effects of changes in recharge to, and discharge from, the ground-water system that are typical of the Eastern Shore (fig. 21). Ground-water levels fluctuated from about 19 ft above sea level in the winter to about 16.5 ft above sea level at cluster WLC300 in the uplands. The altitude of ground-water levels decreased toward the wooded wetlands and saltwater marsh. Seasonal highs in ground-water levels ranged from about 5.5 ft above sea level at cluster WDM30 to about 4 ft above sea level at cluster WDM100 at the edge of the saltwater marsh.

Evapotranspiration appeared to have major effects on ground-water levels in the wooded wetlands and saltwater marsh during the growing season, creating both seasonal and daily cycles in ground-water levels (figs. 21 and 22). When evapotranspiration rates were low during the winter the water table was represented by standing water in wetland parts of the woodlands; when evapotranspiration rates were high, the water table declined to more than 3 ft below land surface, less than 1 ft above sea level beneath parts of the woodlands. As standing water disappeared and water levels declined below land surface, daily rises and falls in ground-water levels were observed with daily highs in the early morning and daily lows near the end of the daylight hours (fig. 22). This cycling was not observed in water levels measured beneath the uplands (cluster WLC300); however, it was observed in wells with water-level recorders in the wetlands (clusters WDM30, WDM50, and WDM100). These cycles resulted from the competing effects of ground-water inflow from the uplands and ground-water discharge by evapotranspiration. The magnitude of the daily cycles increased to as much as 0.75 ft at cluster WDM50, as ground-water levels declined. This possibly resulted from the mechanism by which vegetation withdrew and transpired ground water in wetland areas, a discussion of which is beyond the scope of this report. The daily

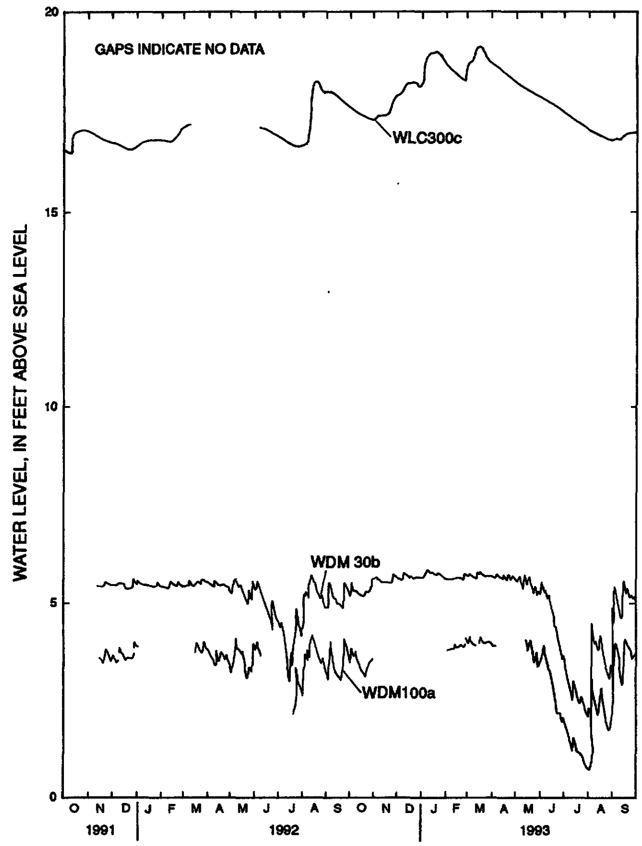


Figure 21. Seasonal fluctuations in water levels in selected wells at the site with coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh, Eastern Shore, Virginia.

cycles in ground-water levels indicate that evapotranspiration was a major pathway for ground-water discharge.

For the 91-day period, June 2, 1993 through August 31, 1993, estimated amounts of evapotranspiration were 25.8 in. at cluster WDM30, 37.6 in. at cluster WDM50, and 10.9 in. at cluster WDM100. These rates may appear somewhat high (particularly when considering that the period for the estimate does not include the entire part of the year when the plants actively transpire) when compared to the 25.12 in/yr of total evapotranspiration estimated by Rasmussen and Andreasen (1959) for an entire watershed in Maryland. High rates of evapotranspiration could be expected from the wooded wetland and saltwater marsh because rates for entire watersheds are averages for the uplands where rates of evapotranspiration can be limited by availability of water and riparian areas along streams where evapotranspiration is not limited by water availability. Estimated rates of

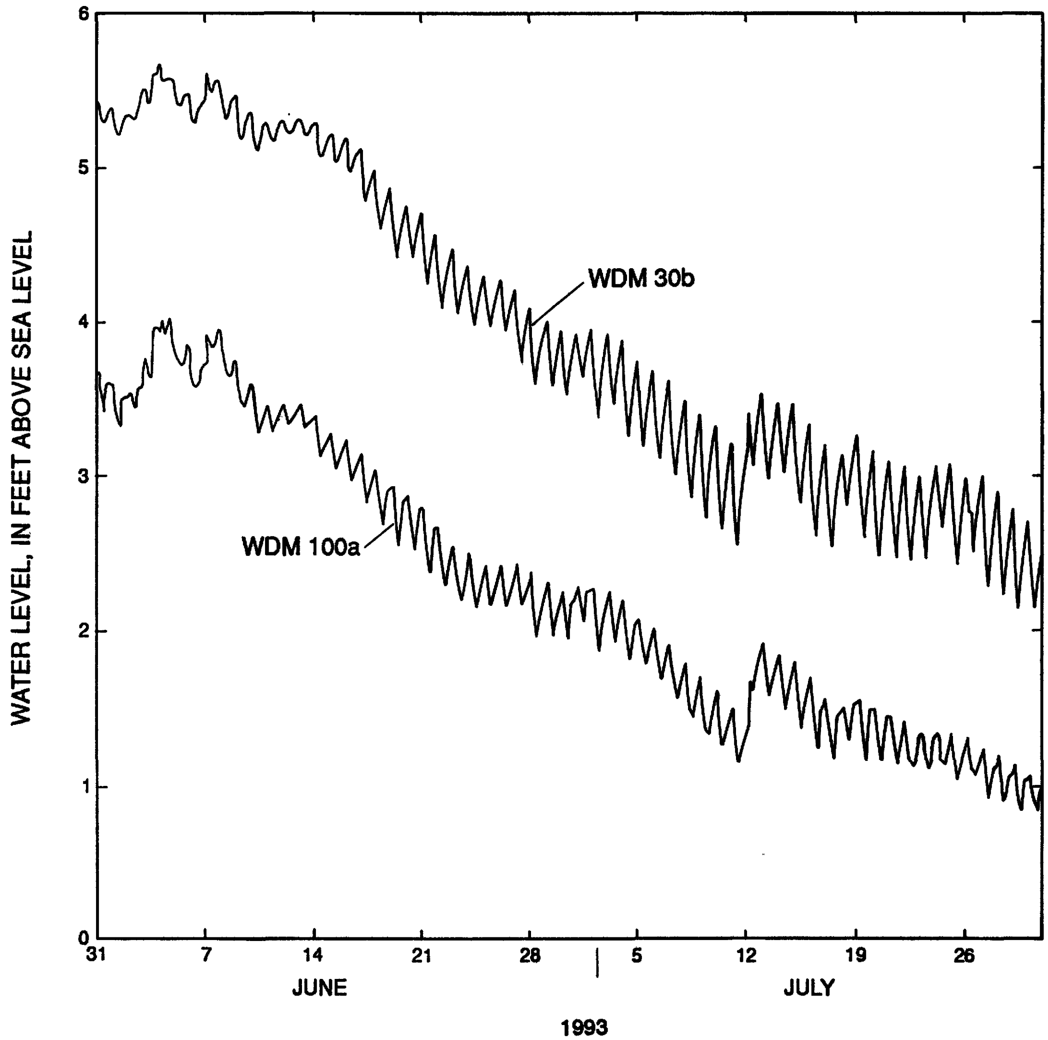
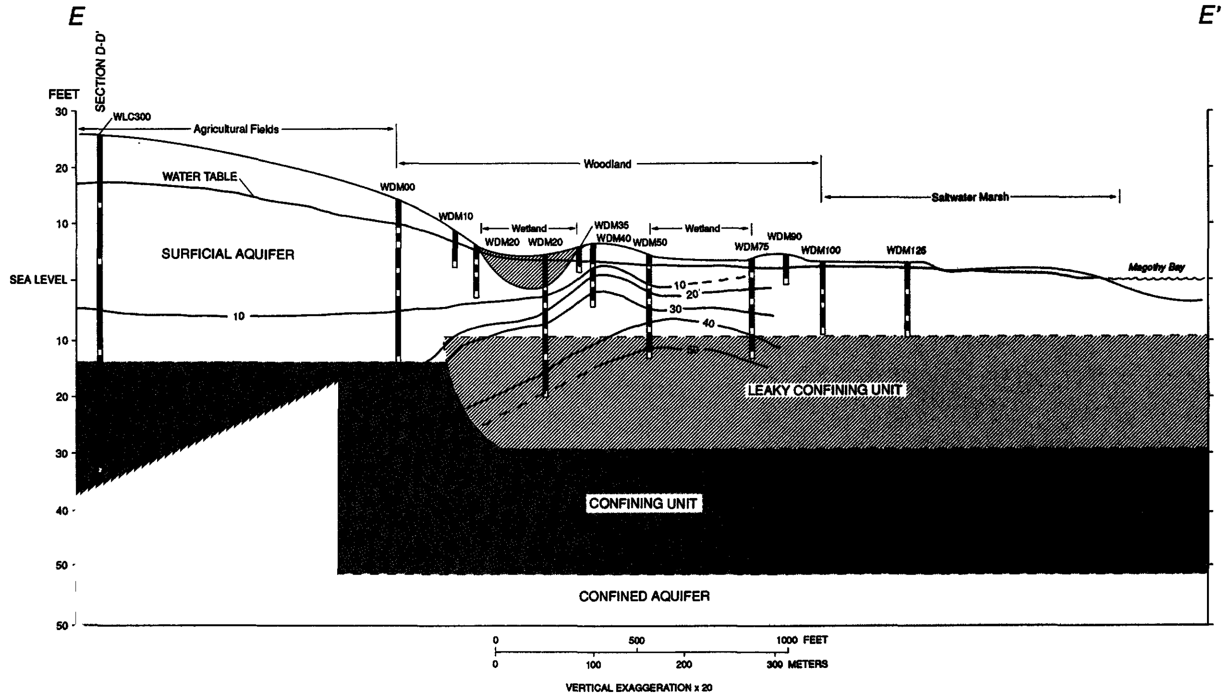


Figure 22. Daily fluctuations in water levels in selected wells at the site with coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh, Eastern Shore, Virginia.

evapotranspiration were greatest in the vicinity of clusters WDM30 and WDM50, where vertical and horizontal hydraulic gradients indicated that ground water discharged from the surficial aquifer to the wetland.

The age of ground water in the surficial aquifer increased with depth beneath the upland from 2 years old to between 10 and 15 years old about 30 ft below the water table (table 1 and fig. 23). Beneath the wetlands, "old water" was much closer to land surface and the water table, and about 15 ft below the water table, water from well WDM50e was more than 53 years old (the greatest age for which the concentration of CFC-12 was detectable). As the age of water increased along a flow path in the surficial aquifer, age gradients would decrease if flow velocities increase. The shallowness of the old water, therefore, probably resulted from discharge of water from the underlying confined aquifer in replacement of water that discharged from the surficial aquifer to the wetland. Ground water in the confined aquifer could be expected to discharge into the surficial aquifer beneath the wetland because the decrease in the altitude of the water-table aquifer from the upland to the lowland would likely create upward hydraulic gradients. Although hydraulic gradients indicate that the wetland is primarily a discharge area, the wetlands can briefly be a recharge area during periods of precipitation and tidal inundation. The presence of younger water in the shallow part of the aquifer beneath the wetland



EXPLANATION

—10— — LINE OF EQUAL GROUND-WATER AGE--Dashed where approximately located. Interval, in years since recharged at the water table, is 10

INDIVIDUAL WELL OR WELL CLUSTER

WDM30 Number

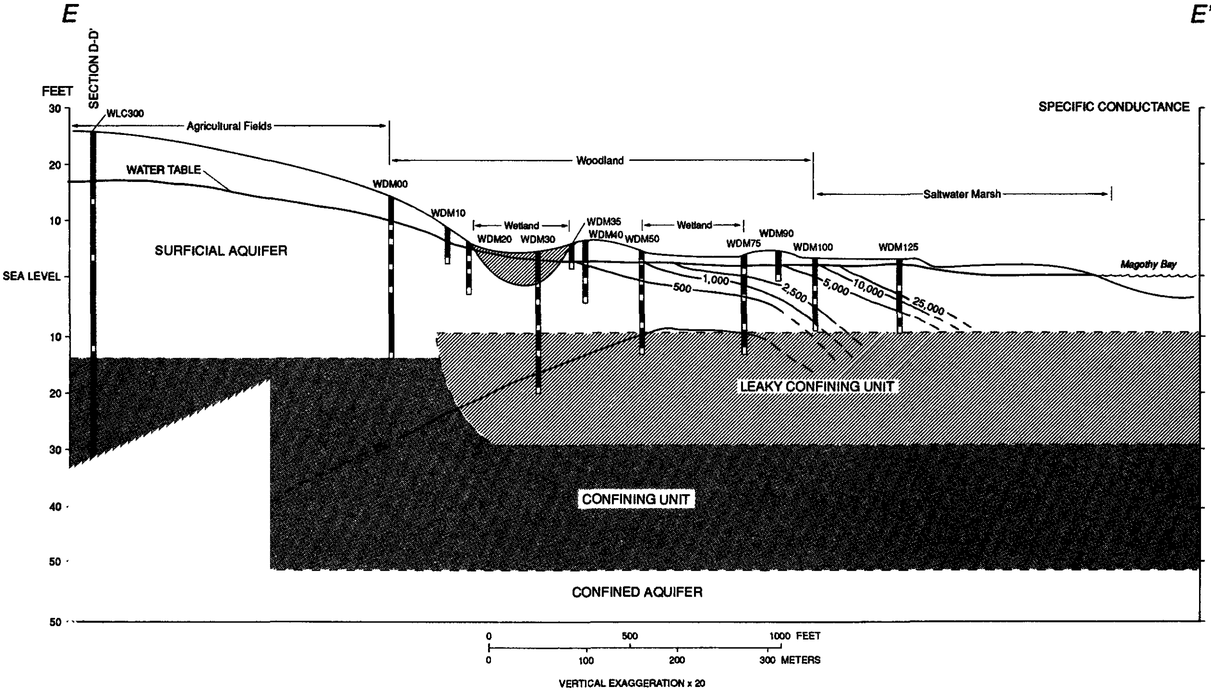
Cased part of wells

2.6-foot-long screened interval--Each screened interval is for a separate well in the cluster

Figure 23. Geohydrologic section showing ground-water age calculated from chlorofluorocarbon concentration at the site with coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh, Eastern Shore, Virginia. (Location of line of section shown on figure 7.)

probably results from mixing young recharge water with older discharging water. Mixing small amounts of young water with large amounts of old water can give a more recent apparent age to the ground water because changes in concentrations of CFC's in the atmosphere are greater in recent years.

Recharge rates estimated from ages of water from wells at cluster WLC300 ranged from 2.7 to 13.3 in/yr with a median rate of 9.6 in/yr (table 1 and fig.11). These rates are greater than the rates for the fine-grained sediments at Leatherberry Creek and are similar to, or greater than, rates for the coarse-grained sediments at Leatherberry Creek. The median rate was about one half of the 21.31 in/yr total ground-water-recharge rate estimated for Beaverdam Creek (Rasmussen and Andreasen, 1959), and slightly more than the average 8.5 in/yr base-flow discharge to streams throughout the Delmarva Peninsula (Cushing and others, 1973). If these rates are representative of the ground-water-recharge rate over the uplands, then the amount of ground water available for discharge can be estimated from the amount of contributing recharge area between the center of the peninsula and the wetland, and the amount of discharge area across the wooded wetland to the saltwater marsh. This recharge area was about 7,500 ft wide; the discharge area was about 1,000 ft wide. Disregarding precipitation that falls directly on the wetland, 9.6 in/yr of recharge to 7,500 ft of uplands is equivalent to 72 in/yr of discharge to the wetland. Adding the approximately 42 in/yr of precipitation that falls on the Eastern Shore (National Oceanic and Atmospheric Administration, 1992), more than 100 in/yr was available for discharge to the wooded wetland, more than the 10.95 to 37.6 in.



EXPLANATION

—10 – – LINE OF EQUAL VALUE OF INDICATED VARIABLE--Dashed where approximately located. Interval is variable. Specific conductance is in microsiemens per centimeter at 25°C, dissolved oxygen is in milligrams per liter, and nitrate nitrogen is in milligrams per liter as nitrogen

INDIVIDUAL WELL OR WELL CLUSTER

WDM30 Number

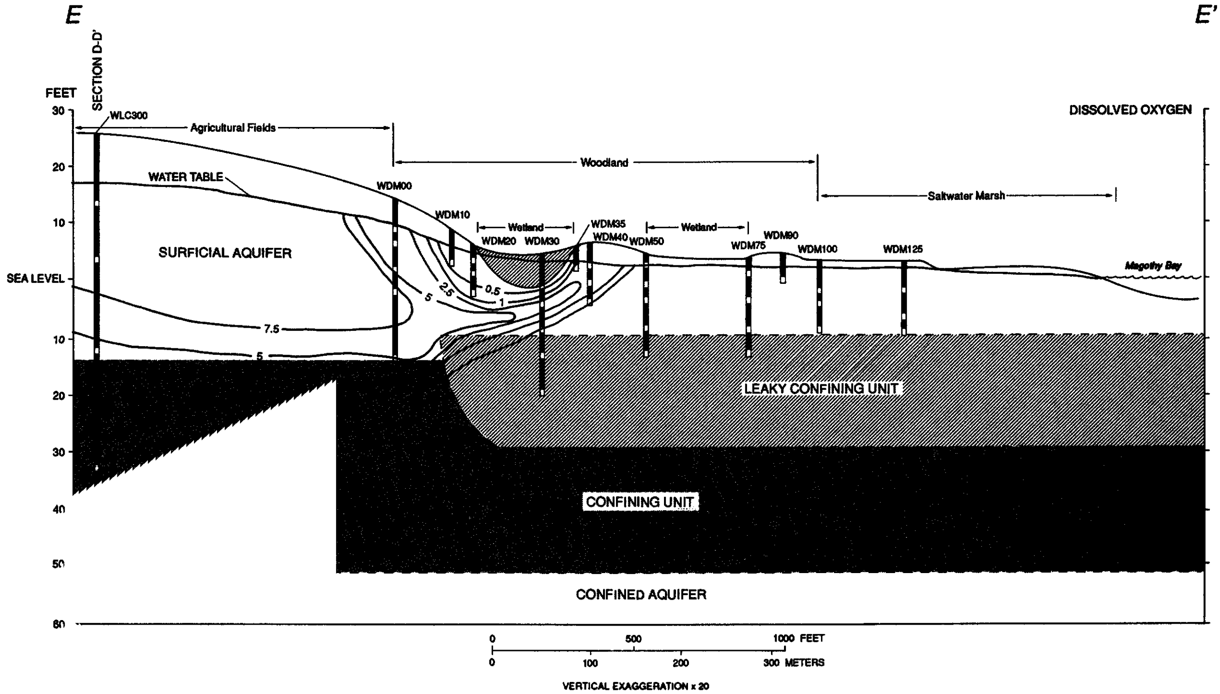
Cased part of wells

2.6-foot-long screened interval--Each screened interval is for a separate well in the cluster

Figure 24. Geohydrologic section showing specific conductance and concentrations of dissolved oxygen and nitrate in ground water at the site with coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh, Eastern Shore, Virginia. (Location of line of section shown on figure 7.)

of evapotranspiration calculated from the water-level hydrographs for the 91 days in 1993.

Water-quality data also support the hypothesis that most of the ground water in the surficial aquifer discharges to the wooded wetland (table 3 and fig. 24). The distribution of specific conductance was affected by ground-water-flow patterns. Ground water beneath the agricultural fields has a specific conductance of 291 to 462 µS/cm (table 3 and fig. 24). Water from wells WDM50e and WDM75e has a specific conductance less than 250 µS/cm and was the oldest water from any of the wells sampled. Specific conductance also indicates that salty water from extremely high tides has flooded parts of the lowlands and recharged the aquifer. This recharge of salty water is indicated by the increase in specific conductance to about 4,950 µS/cm near the water table at cluster WDM75, 6,610 µS/cm at the water table near cluster WDM100, and 28,600 µS/cm near the water table at cluster WDM125. In the wooded wetlands overlying this water, most of the roots of the pine trees and shrubs appear to be in raised hummocks and the growth of pine trees appears to be stunted, indicating that the shallow, salty water is a long-term rather than a short-term condition. The distribution of salty ground water in this part of the surficial aquifer also indicates that ground water flows sluggishly through the aquifer and further supports the concept of ground-water discharge to the wooded wetlands in the vicinity of clusters WDM30 and WDM50, and higher rates of ground-water evapotranspiration in the woodland than in the saltwater marsh.



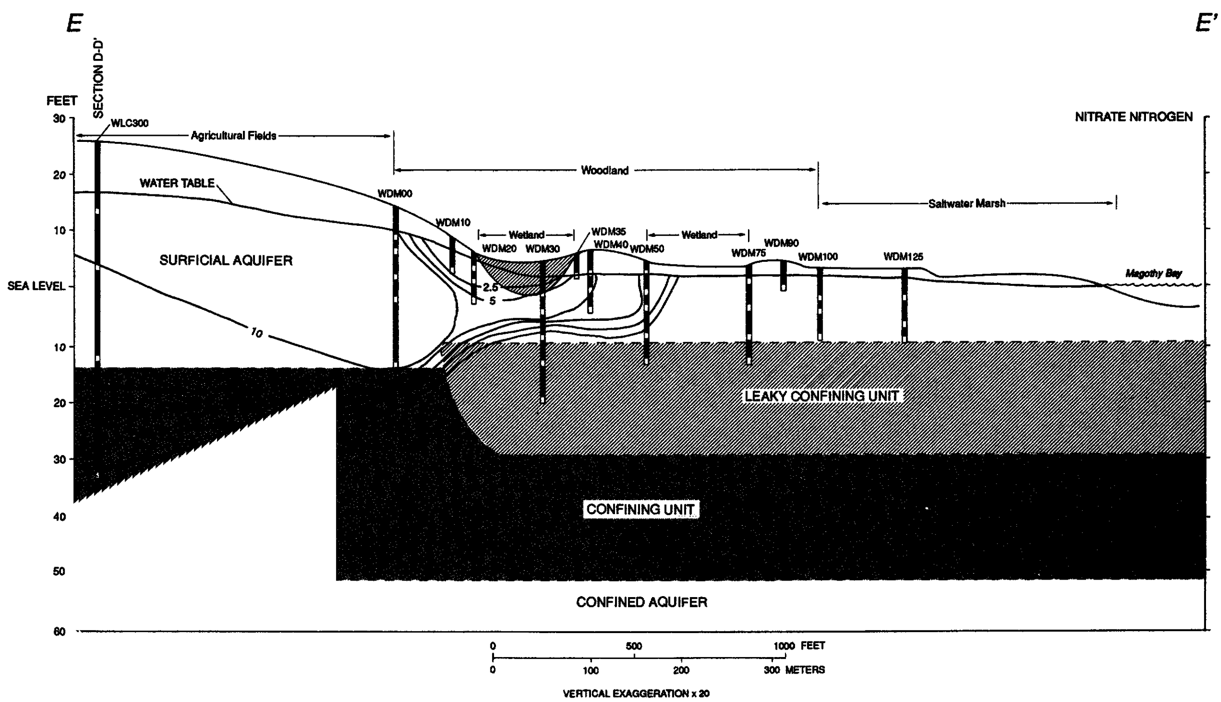


Figure 24.—Continued.

Specific conductance also indicates that no dense saltwater was present at the bottom of the aquifer. Based on the Ghyben-Herzberg relation, no underlying dense saltwater would be expected at the boundary between the wooded wetland and saltwater marsh (cluster WDM100). Saltwater would remain 30 to 160 ft below sea level based on this relation because water levels in well WDM100a ranged from about 0.75 to 4 ft above sea level (fig. 20) and the bottom of the surficial aquifer is about 10 ft below sea level.

Geochemistry

The relative composition of major ions in the ground water indicates that ground water at the Magothy Bay site consisted of one of three water-quality types or a mixture of these types (fig. 25). These differences are evident in the relative anionic composition, and the combined relative anionic and cationic composition. The types of water appear to be closely related to the water sources inferred from specific conductance and the conceptualization of ground-water flow. Salty, high specific-conductance water from shallow parts of the aquifer toward Magothy Bay were dominated by sodium and chloride ions. This water was from wells WDM75b, WDM90b, WDM100a, and WDM100b. Lower ionic-strength water (specific conductance less than 250 µS/cm) from the bottom of the aquifer was dominated by calcium and bicarbonate ions. This water was present only in wells WDM50e and WDM75e. Water from well WDM75d (specific conductance of 300 and 325 µS/cm) appears to be a mixture of a small amount of the salty water from the upper part of the surficial aquifer with a large amount of the lower ionic-strength water that discharged from the confined aquifer based on the slightly elevated specific conductance and concentrations of sodium, chloride, and other ions. The quality of this water was on the mixing line (the straight line drawn between two water types representing various mixtures of the two source waters) between the two sources (fig. 25). Water from well WDM75c was also on the mixing line, but was more similar to the salty water than water from the confined aquifer.

The third type of water appears to be agriculturally affected based on well locations and the elevated concentration of nitrate. This water was dominated by calcium and sulfate-plus-nitrate ions and was withdrawn from all wells open to the surficial aquifer at clusters WLC300 and WDM00 and from wells WDM30b, WDM30c, WDM35a, WDM40b, WDM40c, and WDM50c. Water from wells WDM30d, WDM30e, and WDM50d are on the mixing line between the agriculturally affected water and the lower ionic-strength water; water from well WDM30e was more like the lower ionic-strength water than water from the other two wells. Water from well WDM50b appears to be on the mixing line between the agriculturally affected water and the salty water, which is consistent with the slightly elevated concentrations of sodium and chloride in water from this well (table 2) and the specific conductance greater than 1,000 µS/cm in water from well WDM50a (the shallowest well at cluster WDM50) when water-level altitudes were high. Water from wells WDM10b, WDM20b, and WDM20d also differ slightly from the agriculturally affected water (table 2 and fig. 25). Water from wells WDM10b and WDM20b was of similar quality to that of water from well WDM50b with chloride concentrations of 55 and 60 mg/L, respectively. Water from these wells contains small amounts of dissolved salt either from recharge by saltwater from a historic extremely high tide or from evaporation of surface runoff from the agricultural fields to the woodland before it recharged the ground water.

These water-quality relations further support previously described concepts of ground-water flow beneath the wooded wetland and saltwater marsh (fig. 26). Salty water has recharged the surficial aquifer from land surface. The effects of this recharge increase toward Magothy Bay and were present in the shallowest part of the surficial aquifer at least as far inland as cluster WDM50. The source of the effects on the quality of water from well WDM10b and at cluster WDM20, partly were from recharge of agricultural runoff from the field through the woodland soils. Agriculturally affected ground water flows from beneath the fields under the wooded wetland as far as cluster WDM50. Lower ionic-strength water discharges upward from the confined aquifer into the lower part of the surficial aquifer at clusters WDM50 and WDM75. Lower ionic-strength water mixes from the bottom of the surficial aquifer with the salty water near the water table at cluster WDM75 and with agriculturally affected water at clusters WDM30 and WDM50. This mixing of old, lower ionic-strength water with younger salty water and agriculturally affected water can account for the sharp gradient in

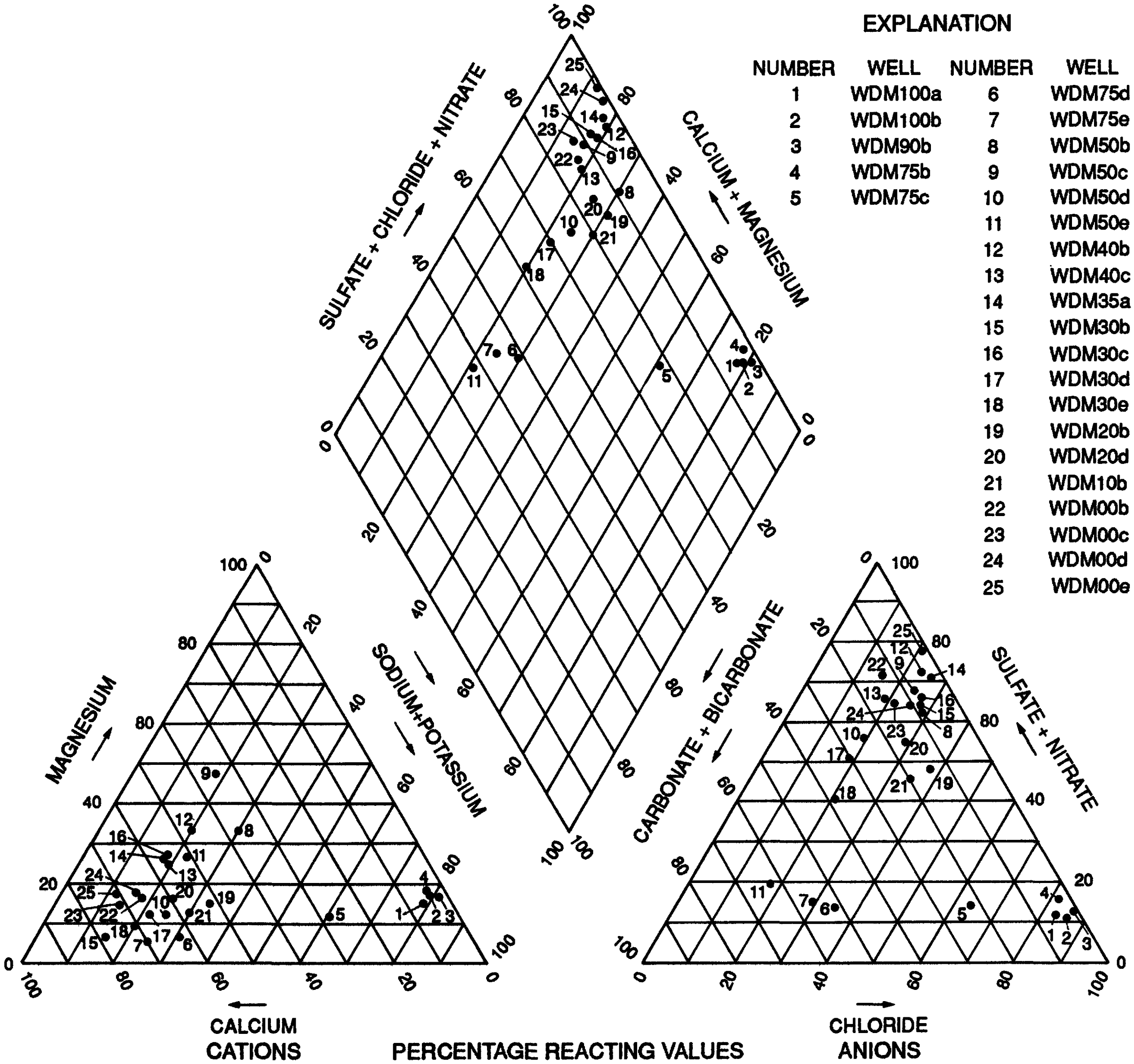


Figure 25. Relative ionic composition of ground water at the site with coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh, Eastern Shore, Virginia.

ground-water age beneath the wooded wetland (fig. 23).

The water-quality relations indicated that all of the agriculturally affected water discharged from the surficial aquifer before cluster WDM75, and all the ground water that remained in the aquifer was locally recharged salty water and a small amount of water discharging from the confined aquifer. The discharge of agriculturally affected ground water is consistent with the relative decrease in horizontal hydraulic gradient from a median of 0.0070 between clusters WLC300 and WDM00 to a median of 0.0005 between clusters WDM50 and WDM75. Discharge from the confined aquifer probably is small because it only receives about 0.6 in/yr of recharge (Richardson, 1994).

The distribution in the concentration of dissolved oxygen reflects a combination of the effects of ground-water-flow paths and changes in the organic content of the aquifer sediments (fig. 24). Because of the varied depositional environment, the Wachapreague Formation contains a variable organic content. The organic content of sediments at cluster WDM30 ranged from 0.2 to 2.5 gm/kg (table 6). The concentration of dissolved oxygen generally remained above 5 mg/L in water from wells in the surficial aquifer beneath the agricultural fields (table 3 and fig. 24). A concentration of dissolved oxygen greater

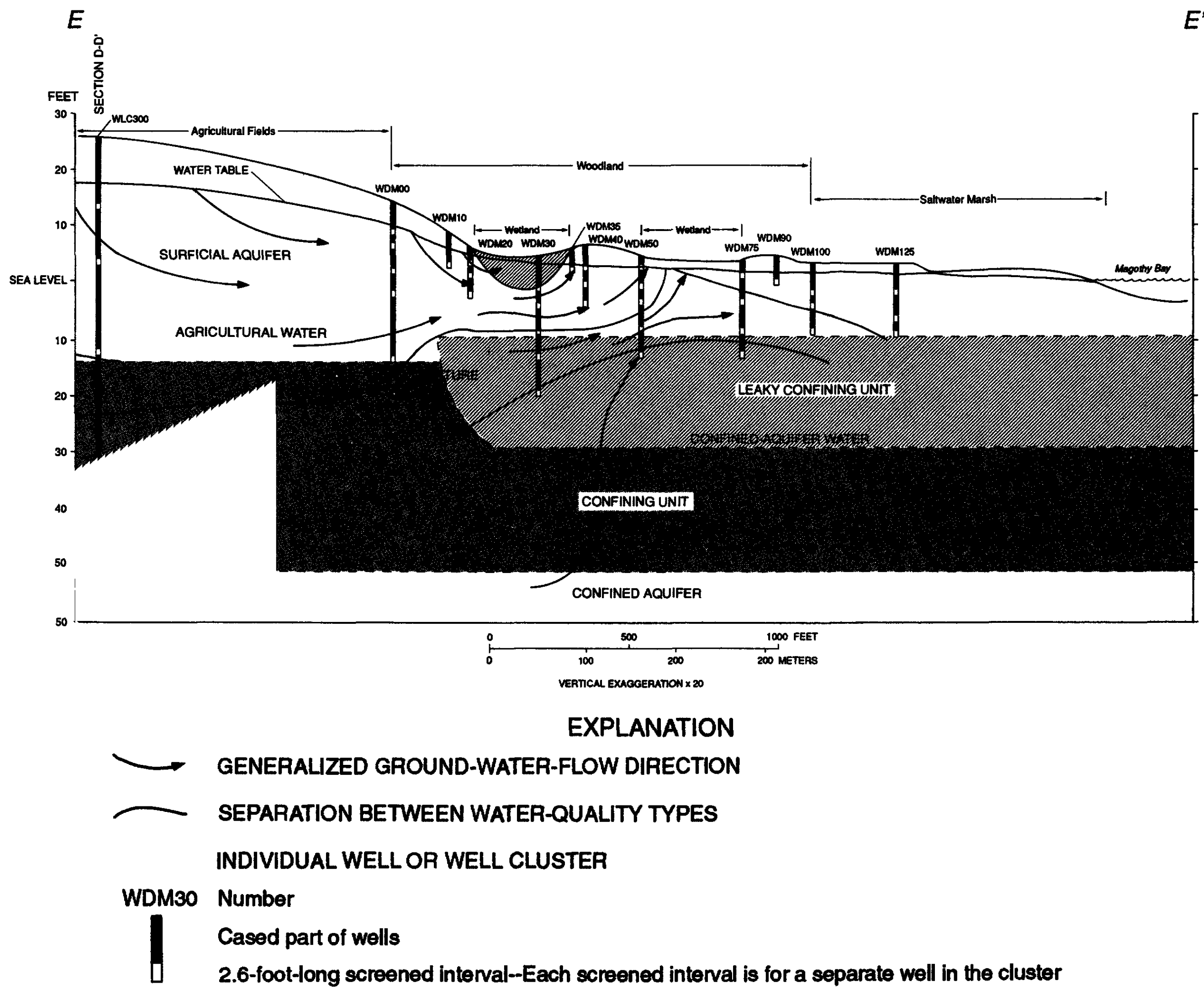


Figure 26. Geohydrologic section showing sources of ground water and generalized ground-water-flow directions at the site with coarse-grained upland sediments adjacent to a wooded wetland and saltwater marsh, Eastern Shore, Virginia. (Location of line of section shown on figure 7.)

than 2.5 mg/L extended past cluster WDM30 to more than 500 ft beneath the woodland; however, the dissolved oxygen concentration was less than 0.5 mg/L in ground-water recharge that infiltrated through the riparian woodland near the edge of the field (wells WDM10b and WDM20b). A concentration of dissolved oxygen greater than 1 mg/L extended past cluster WDM40 to more than 650 ft into the woodland. The concentration of dissolved oxygen was less than 0.5 mg/L at cluster WDM50, about 850 ft into the woodland. The concentration of dissolved oxygen generally was less than 0.5 mg/L in ground water that discharged from the underlying confined aquifer and in salty water that recharged the aquifer in the wooded wetland. The low concentration of dissolved oxygen in the salty recharge probably resulted from the combined effects of the organic content of surficial soils and sediments of the Wachapreague Formation; the fine-grained sand that underlies the hummocks between clusters WDM50 and WDM75 appears to contain abundant organic material that was probably deposited when the sand was deposited.

The concentration of nitrate in ground water in the surficial aquifer beneath the agricultural fields (clusters WLC300 and WDM00) ranged from 7.8 to 22 mg/L as N (table 3 and fig. 24). The elevated nitrate concentration extended beneath the woodland; a nitrate concentration of 5 mg/L as N extended more than 650 ft into the woodland, past cluster WDM40, although the nitrate concentration was only 2.1 mg/L

Table 6. Content of inorganic carbon, total carbon, and organic carbon in sediment samples from well clusters WDM30 and WLC00, Eastern Shore, Virginia

[ft, feet; gm/kg, grams per kilogram; <, less than]

Sample depth	Well cluster								
	WDM30						WLC00		
Top (ft)	**5.5**	**7.2**	**10.0**	**11.0**	**12.0**	**14.0**	**0.0**	**2.5**	**6.0**
Bottom (ft)	**6.7**	**10.0**	**11.0**	**12.0**	**14.0**	**23.5**	**2.5**	**6.0**	**9.1**
Inorganic carbon (gm/kg)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Total carbon (gm/kg)	2.5	.4	.6	.3	.2	.3	17	81	.3
Organic carbon (gm/kg)	2.5	.4	.6	.3	.2	.3	17	81	.3

as N in ground-water recharge that recharged through the riparian woodland near the edge of the field (wells WDM10b and WDM20b). A nitrate concentration of 2 to 3 mg/L extended more than 850 ft into the woodland to cluster WDM50. The nitrate concentration was near, or less than, the detectable concentration in salty water recharged in the wooded wetlands, in water discharged from the confined aquifer, and in water that had a low concentration of dissolved oxygen and was a mixture of agriculturally affected water and water discharged from the confined aquifer. Salty water that recharged the surficial aquifer beneath the woodland would contribute little nitrate to the ground-water system because seawater is normally low in nitrate. The concentration of nitrate in the agriculturally affected water decreased as the concentration of dissolved oxygen decreased. Because ground water flows upward and discharges to the wetland, the organic content of the wooded wetland soils is not likely to affect the concentrations of organic carbon and dissolved oxygen in the ground water (except near the water table). Water with an elevated concentration of nitrate extended through the area where agriculturally affected ground water appears to flow but did not extend beyond where this ground water discharged to the surface.

Implications of the Geohydrology and Geochemistry on Land-Use Management Practices

The geohydrologic and geochemical processes beneath agricultural fields and the riparian woodland to which ground water discharged at the Magothy Bay site have important implications on land-use management practices. These processes affect the quality and flow of water that infiltrated through fields and recharged the surficial aquifer differently than water that infiltrated through the woodlands and recharged the surficial aquifer. Water that infiltrated through the fields contained an elevated concentration of nitrate; the concentration of nitrate remained elevated in this water as it flowed more than 850 ft into the riparian woodland and discharged. Decreases in the concentration of nitrate toward the end of the flow path appear to have been caused by denitrification where the concentration of dissolved oxygen approached 0 mg/L, as ground water flowed through localized parts of the Wachapreague Formation that contain abundant organic material. Based on ground-water-flow paths, these changes in nitrate concentration appear to result primarily from changes in the organic content of the sediments that resulted from sediment deposition, not the current presence of the riparian woodland. Thus, the presence of such geochemical processes that result from the organic content of the sediments, not the presence of riparian woodland, are an important consideration for incorporation with land-use management practices.

Although the riparian woodlands probably had little, if any, role in decreasing the concentration of nitrate in the ground water that flowed beneath the riparian woodland from the fields, the riparian woodland probably had a major role in reducing the load of nitrate and other nutrients that discharged to the estuary along other pathways. For this reason, riparian woodlands continue to have an important role in land-use management practices. These roles can influence decisions on how riparian woodlands are managed. Woodlands remove sediment and nutrients in surface runoff, as shown in other studies, but have additional functions that protect the quality of surface waters. As a result of the woodland function in improving the quality of surface runoff, the quality of runoff that infiltrates through the woodland soils and recharges the surficial aquifer will be affected by geochemical processes in the woodland soils. One of these processes is denitrification of nitrate, as indicated by the high denitrification potential in woodland soils identified in other studies (Lowrance, 1992). A second process is ground-water evapotranspiration and nitrate uptake by woodland vegetation. Much of this uptake appears to be in the wetland part of the woodland. Even without the woodland, ground water would discharge to the surface because of the decrease in saturated thickness of the aquifer, and the decrease in the horizontal hydraulic gradient that results, in part, from the low topographic gradient. Thus, without sufficient discharge through evapotranspiration, water would discharge to the surface waters as overland flow after it discharges to land surface. Although no overland flow was observed from the wetland to adjacent creeks and Magothy Bay, ground water that discharges to the surface can flow along such pathways. Several wetlands-management practices could affect the transport of discharged ground water by overland flow to the estuaries. Ditching of wetlands creates short-circuit pathways for nitrate-rich water to discharge from the wetlands to the estuaries; thus, filling existing ditches and not digging new ditches would minimize future discharge of nitrate-rich water to the estuaries. Cutting trees in these wetlands would reduce rates of evapotranspiration and would cause standing water levels to rise, possibly causing discharge by overland flow to the estuaries through naturally low areas through which flow does not normally occur. Such effects could last for years after trees are cut until mature vegetation was reestablished and high rates of evapotranspiration were restored.

The thickness and hydraulic properties of the aquifer and the width and topography of riparian woodlands can affect whether or not ground water discharges to an estuary. At this site, agriculturally affected water does not appear to discharge to the estuary. Where the saturated thickness of the surficial aquifer is greater than at this site, more ground water can flow through the aquifer, and the ground water can possibly flow farther through the aquifer. Where the distance between the upland and the estuary are less, hydraulic gradients could be greater than at this site, and ground water would flow farther beneath the wetland. Consequently, although agriculturally affected ground water flowed beneath the wetland for more than 850 ft at this site, ground water could flow considerably greater distances depending on geohydrologic conditions. Even without such differences in system configurations, data from this site indicate that agriculturally affected ground water would discharge to the estuary if it were within 850 ft of the uplands, a considerably greater distance than the buffer widths of 50 to 300 ft that are commonly thought to remove nitrate from ground water (Lowrance, 1992; Gilliam, 1994).

Results from the Magothy Bay site indicates that in the appropriate geohydrologic setting, wooded wetlands and saltwater marshes can provide an effective zone to minimize the discharge of ground water that has elevated nitrate or other contaminants from beneath an upland to an estuary. However, land-surface altitude (as it affects hydraulic gradient and the thickness of the surficial aquifer), the type, size, and distribution of vegetation; the organic-carbon content of the aquifer; and the hydraulic properties of the aquifer can affect the width of the area needed to prevent or reduce discharge of nitrate-rich ground water to the estuary. Land-use management practices can alter the ability of such an area to prevent or reduce the discharge of nitrate-rich ground water to the estuary.

The types of land-use management practices needed in the uplands to reduce the leaching of nitrate into ground water and subsequent discharge to an estuary will depend on the width of the riparian woodland and the local geohydrology and geochemistry. Where lowlands with increased organic content in the deep sediments and woodlands are not sufficiently wide for nitrate to denitrify or for ground water with elevated nitrate to be removed by evapotranspiration, zoning and management practices that reduce the loading of nitrate to the ground water would be needed to reduce the loads of nitrate that flows beneath the riparian woodland and discharges to the estuary. Such zoning and management practices could include low-density residential development that would reduce the density of septic tanks and controlling the amount, timing, and type of fertilizer applied to fields and residences in order to minimize leaching of nitrate to the ground water. Where lowland woodlands are sufficiently wide to remove nitrate by plant uptake or denitrification, residential density can be greater and the timing, rate, and type of fertilizer application are not as critical for controlling the discharge of nitrate to an estuary.

Ground Water Discharging from Coarse-Grained Upland Sediments to a Nontidal Creek (Walls Landing Creek)

Geohydrologic and geochemical processes significantly changed the concentration of nitrate as ground water flowed through sediments deep beneath the riparian woodland and discharged to Walls Landing Creek. Although the processes depend on the local geohydrologic and geochemical environments, many processes adjacent to other nontidal creeks will be similar.

Geohydrology

Ground-water levels reflected the seasonal effects of recharge to, and discharge from, the ground-water system typical of the Eastern Shore (fig. 27). Ground-water levels in the uplands (well WLC300e) ranged from a high of about 19 ft above sea level in the winter to a low of about 16.5 ft above sea level in the summer. Seasonal fluctuations were only about 1 ft from the edge of the field (cluster WLC100) across the flood plain (clusters WLC75 and WLC50) to the edge of the creek (cluster WLC00). Water levels decreased from about 12.5 to 13.5 ft above sea level at cluster WLC100 to about 11.5 to 12.5 ft above sea level at cluster WLC00.

Horizontal hydraulic gradients were small between cluster WLC300 and well WLC175a, with a median value of 0.0004 (fig. 28). Median horizontal gradients increased to 0.0037 between wells WLC175a and WLC150a and continued to increase to a maximum of 0.0066 between clusters WLC100 and WLC75 before decreasing to about 0.0030 among clusters WLC75, WLC50, and WLC00. The horizontal gradient between cluster WLC300 and well WLC175a was small when compared to the gradient between wells WLC175a and WLC150a, indicating that little ground water flowed from cluster WLC300 toward well WLC175a and Walls Landing Creek, and that the primary source of ground-water recharge to Walls Landing Creek was between well WLC175a and the creek. Ground water primarily flowed from cluster WLC300 toward cluster WDM00 and the saltwater marsh because the median horizontal gradient between clusters WLC300 and WDM00 (on a line approximately perpendicular to the line between cluster WLC300 and well WLC175) was 0.0070 (fig.19), approximately seventeen and a half times as large as the median horizontal gradient between cluster

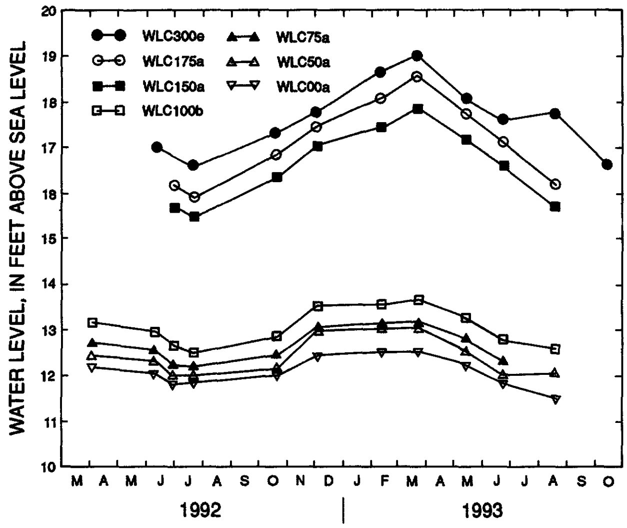


Figure 27. Water levels in selected wells at the site with coarse-grained upland sediments adjacent to a nontidal creek, Eastern Shore, Virginia.

WLC300 and well WLC175. Consequently, the area from which ground water flowed toward Walls Landing Creek appears to be small. Although little ground water flowed from cluster WLC300 to Walls Landing Creek, water from wells at this cluster probably is representative of water beneath the fields that flowed toward the creek.

Vertical hydraulic gradients at the well clusters showed mixed patterns (fig. 28). Vertical hydraulic gradients were downward in the middle of the field (cluster WLC300), and gradients varied between downward and upward at the edge of the field (cluster WLC100). Vertical gradients were upward in the first part of the area with riparian woodland (cluster WLC75), varied between downward and upward half way between the edge of the field and Walls Landing Creek (cluster WLC50), and were upward at the edge of the creek (cluster WLC00). These vertical gradients indicate that the area of riparian woodland can serve as a recharge or discharge area depending on local hydrologic conditions. Ground water can discharge as seeps or as evapotranspiration. Standing water during periods of high ground-water levels in the vicinity of cluster WLC75 appeared to represent the water table. Surface runoff from the fields to the riparian woodland resulted from heavy rainfall as indicated by the bending of short vegetation and erosion of surface sediments noted after such rainfall. Thus, part of the recharge in the riparian woodland probably included runoff from the fields and would likely contain

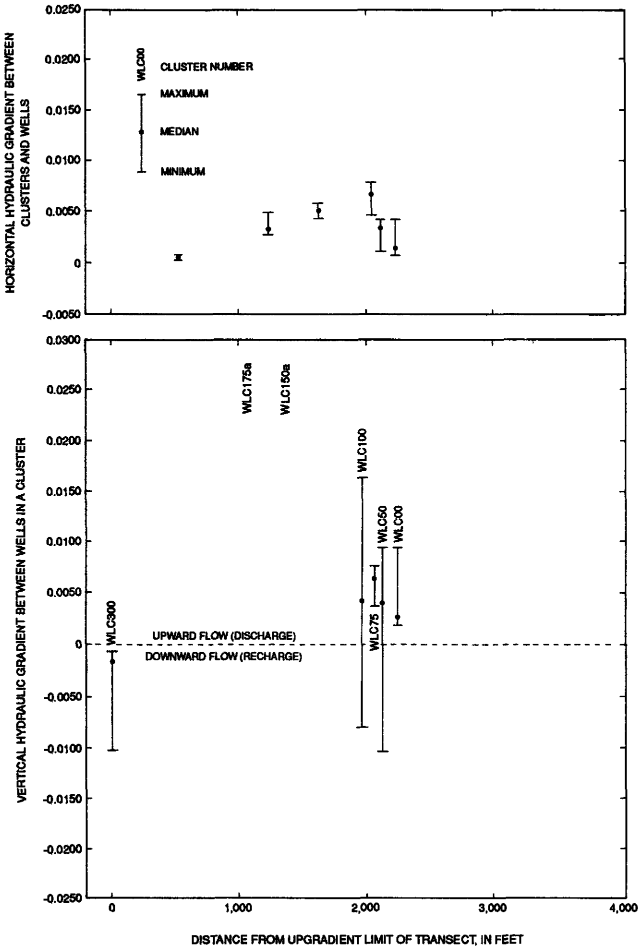


Figure 28. Horizontal and vertical hydraulic gradients at the site with coarse-grained upland sediments adjacent to a nontidal creek, Eastern Shore, Virginia. (Negative vertical gradients are downward and positive vertical gradients are upward.)

agricultural chemicals. Although vertical gradients were downward part of the time at cluster WLC50, the rate of recharge in this area may be slow because the surficial sediments contain abundant silt and clay.

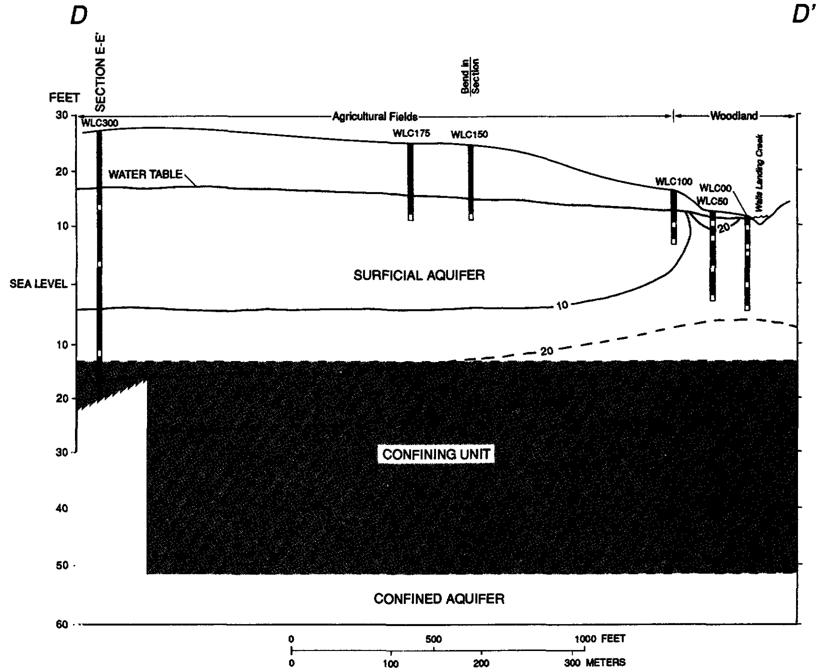
Much of the ground-water probably discharged to the Walls Landing Creek as base flow. After a 4-in. diameter PVC pipe was driven about 2.5 ft into the creek bed adjacent to cluster WLC00 and sediment was augered from inside the casing, the water level inside the casing rose 0.49 ft above the level of the creek. This is equivalent to an upward gradient of about 0.2000, more than ten times the maximum upward gradient observed at any cluster.

The age of the ground water in the surficial aquifer increased with depth from 2 years old to between 10 and 15 years old at cluster WLC300 (table 1 and fig. 29). Because the wells are shallow and the sediments are permeable at cluster WLC100 ground water is relatively young. The age of water beneath the flood plain and riparian woodland ranged from 11.5 to 20.0 years. The oldest water from all wells at clusters WLC00 and WLC50 was in the shallowest wells at each cluster, because the silty and clayey sediments near land surface retard ground-water recharge and lateral flow in the shallow part of the aquifer. Beneath this zone, ground-water age increased with depth from 11.5 to 18.0 years old at cluster WLC00 and from 16.5 to 19.5 years old at cluster WLC50. Age did not increase along the general ground-water-flow path; water from wells at cluster WLC00 was slightly younger than water from wells at cluster WLC50 although the difference was little more than the accuracy of the measurement technique. These clusters are not exactly on a regional ground-water-flow path, therefore, local variability in the flow system can transport ground water more rapidly along certain flow paths than others.

Geochemistry

The dissolution or chemical alteration of sediments beneath the lowlands adjacent to Walls Landing Creek increased the concentration of dissolved constituents in the water, as indicated by specific conductance. The specific conductance of water from wells at cluster WLC300 ranged from 291 to 431 µS/cm (table 3 and fig. 30). Water from these wells probably represents the combined effects of land use and natural geochemical processes on the quality of water that flowed through sediments of the Joynes Neck Formation. Specific conductance of the water increased to between 488 and 587 µS/cm at cluster WLC50 and between 568 and 615 µS/cm at cluster WLC00, which compares to a specific conductance of 440 µS/cm in Walls Landing Creek at the time of the measurements. Consequently, the mineral content of the sediments that underlie the flood plain and riparian woodland appears to differ from the mineral content of sediments that underlie the uplands as indicated by changes in specific conductance over such a short distance.

These differences in the sediment mineral composition do not appear to extend along the entire creek valley as indicated by the soil types and specific conductance of water from Walls Landing Creek. The Polwana sandy loam that lies beneath the flood plain decreases in extent upstream of the study site (Cobb



EXPLANATION

—10– – LINE OF EQUAL MODELED AGE--Dashed where approximately located. Interval, in years since recharged at the water table, is 10

INDIVIDUAL WELL OR WELL CLUSTER

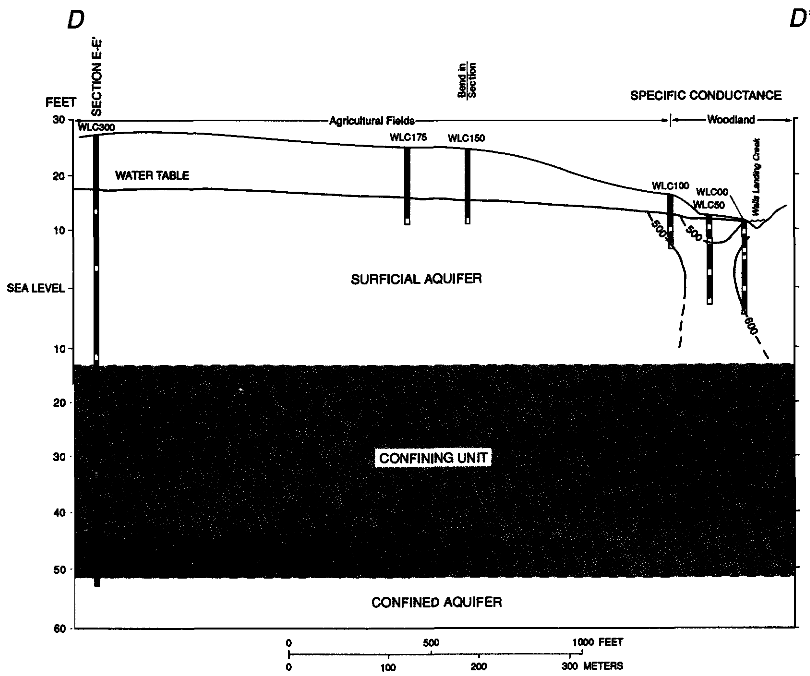
WLC00 Number

Cased part of wells

2.6-foot-long screened interval--Each screened interval is for a separate well in the cluster

Figure 29. Geohydrologic section showing ground-water age calculated from chlorofluorocarbon concentration at the site with coarse-grained upland sediments adjacent to a nontidal creek, Eastern Shore, Virginia. (Location of line of section shown on figure 7.)

and Smith, 1989) and may be indicative of the composition of the underlying sediments. Specific conductance of the creek increased downstream from 291 µS/cm, where the creek crosses State route 600, to 355 µS/cm at cluster WLC00 (a distance of about 2,240 ft) when the well was installed on March 31, 1992, but showed no systematic change on April 1, 1992, from cluster WLC00 to a point another 1,320 ft downstream (fig. 31). Upland fields end adjacent to this downstream point, and lowland, wooded wetlands and saltwater marshes surround the creek beyond this point. Also at this time, the specific conductance of water bailed from the 4-in. diameter PVC pipe that was driven into the creek bottom was 582 µS/cm (unpublished data on file in the Virginia District office of the U.S. Geological Survey). The increased specific conductance appears primarily to result from increased concentrations of calcium, alkalinity, and sulfate rather than from effects of dilute saltwater because concentrations of sodium and chloride changed little (table 2). Changes in specific conductance do not appear to result from the effects of ground water discharging from the underlying confined aquifer because the age of the ground water did not significantly increase toward the creek or with depth, where the effects of such a discharge would be greatest, and the quality of the deeper water in cluster WLC00 was different than that discharging from the



EXPLANATION

—500- - LINE OF EQUAL VALUE OF INDICATED VARIABLE--Dashed where approximately located. Interval is variable. Specific conductance is in microsiemens per centimeter at 25°C, dissolved oxygen is in milligrams per liter, and nitrate nitrogen is in milligrams per liter as nitrogen

INDIVIDUAL WELL OR WELL CLUSTER

WLC00 Number

Cased part of wells

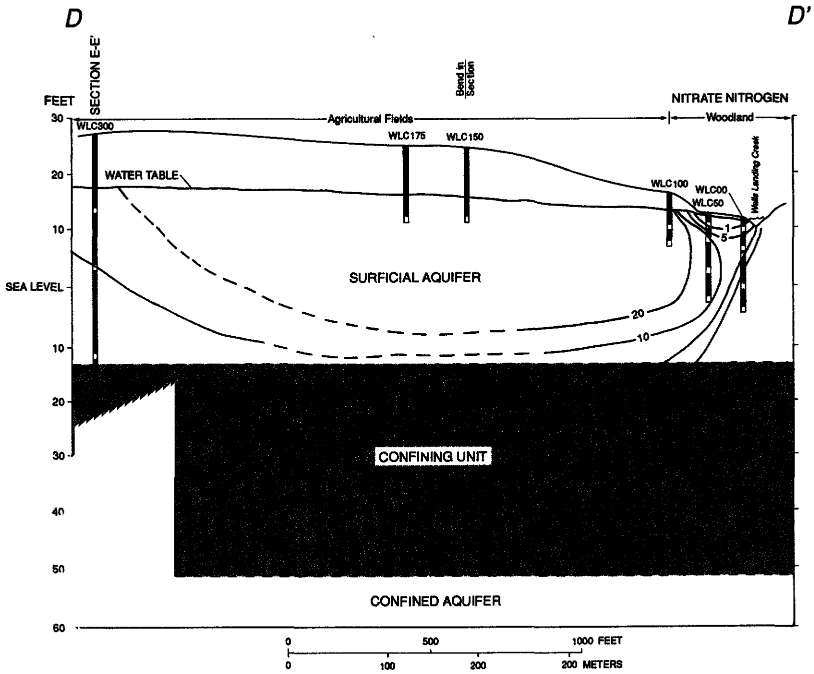
2.6-foot-long screened interval--Each screened interval is for a separate well in the cluster

Figure 30. Geohydrologic section showing specific conductance and concentrations of dissolved oxygen and nitrate in ground water at the site with coarse-grained upland sediments adjacent to a nontidal creek, Eastern Shore, Virginia. (Location of lines of section shown on figure 7.)

confined aquifer in wells WDM50e and WDM75e of the nearby transect that extends across the wooded wetland to the saltwater marsh (table 2).

The relative composition of major ions in the ground water shows small, but distinct, changes as the ground water flowed from the field to the creek (fig. 32). Calcium and sulfate plus nitrate were the dominant ions in ground water at the edge of the field (cluster WLC100). The calcium concentration increased toward the creek, so that calcium remained the dominant cation. The concentration of sulfate increased toward the creek, but the concentration of bicarbonate increased even more, causing a shift in relative anionic composition of the water toward a greater dominance of carbonate-plus-bicarbonate ions although sulfate plus nitrate remained the dominant anions. This slight change in the relative composition of the ground-water quality results from geochemical interaction between the ground water and aquifer minerals.

The organic content of the sediments also appears to change as indicated by the decrease in the concentration of dissolved oxygen from more than 5 mg/L at the edge of the field (cluster WLC100) to



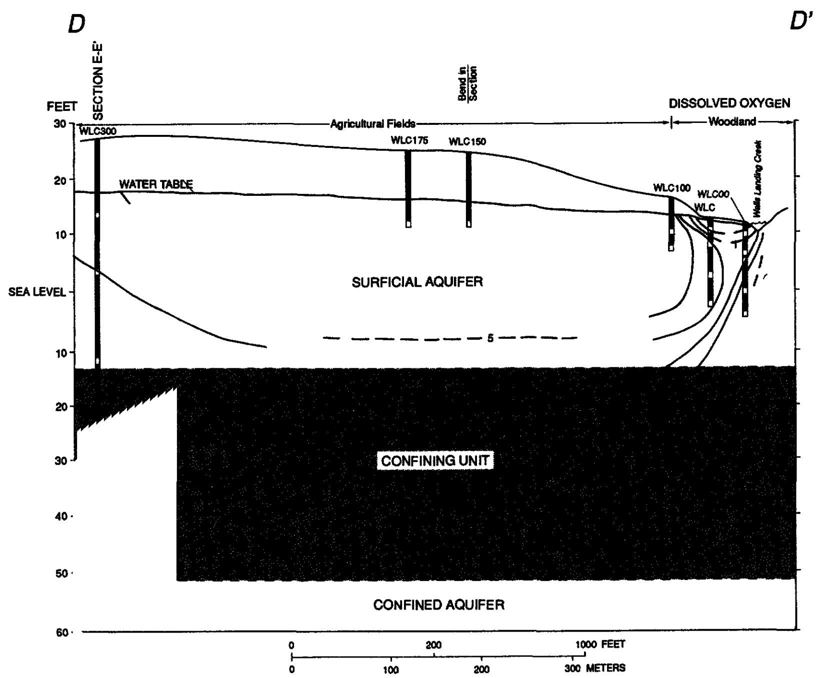


Figure 30.—Continued.

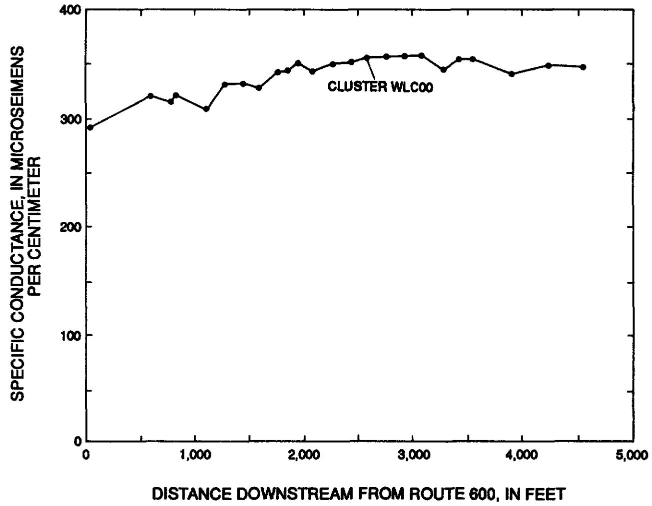


Figure 31. Specific conductance of water from Walls Landing Creek upstream and downstream from well cluster WLC00 measured on March 31 and April 1, 1992, Eastern Shore, Virginia.

1.0 to less than 0.1 mg/L at cluster WLC00 (table 3 and fig. 30). Halfway from the edge of the field to the creek, (cluster WLC50) the concentration of dissolved oxygen remained near 5 mg/L, except in the shallowest well (WLC50a). This well is open to an upper layer of dark brown to light gray, fine-grained sand, silt, and clay that appears to contain abundant organic material. At cluster WLC00 the concentration of organic carbon in sediments between land surface and 2.5 ft below land surface was 17 gm/kg and from 2.5 to 6.0 ft was 81 gm/kg (table 6). The interval between 2.5 and 6.0 ft deep consists of tan and gray, fine-grained sand with zones of gravel that were distinctly different from the overlying soils. Thus, the decrease in the concentration of dissolved oxygen from about 5 mg/L to less than 1.0 mg/L, as ground water flowed about 125 ft laterally, appears to result from an increase in the organic content of the sediments. Because of the homogeneous appearance of the distribution of organic material in the sediments and the depth of the sediments, the increase in organic material probably results from the original deposition of the sediments and is not significantly affected by the current presence of riparian vegetation.

The concentration of nitrate reflects the effects of changes in the concentration of dissolved oxygen. The concentration of nitrate ranged from 6.6 to 21 mg/L as N in water with the concentration of dissolved oxygen greater than 1 mg/L and from <0.05 to 6.0 mg/L as N in water with the concentration of dissolved oxygen equal to, or less than, 1 mg/L (table 3 and fig. 30). In water from well WLC00e, the concentration of excess nitrogen gas was approximately 11.4 mg/L, exceeding the concentration contributed by the atmosphere, as indicated by the concentration of argon gas (table 4); and the concentration of nitrate was 0.091 mg/L (table 3), indicating that most of the nitrate had denitrified to nitrogen gas. Nitrate in water from well WLC50a was less than the detectable concentration although the concentration in deeper wells at the cluster ranged from 9.7 to 14 mg/L. It is uncertain whether the low concentration of nitrate in water from well WLC50a was from denitrification of nitrate along a ground-water-flow path, recharged water with a naturally low concentration of nitrate, or denitrification of surface runoff from the fields that recharged through woodland soils that contain abundant organic material. It is possible that the low concentration of nitrate results from denitrification because the chloride concentration was 40 mg/L, indicating the possible effect of agricultural chemicals. It is also possible that the denitrification would be of recharging surface runoff because physical evidence of surface runoff was present through the woodlands after heavy rainfall. Regardless of the cause of the low concentration of nitrate in WLC50a, water with an elevated concentration of nitrate flowed deeper beneath the riparian woodland at this cluster.

The concentration of nitrate in water from wells at cluster WLC00 generally was lower than the concentration in water from wells at any other cluster, ranging from less than the detectable concentration to 6.0 mg/L; however, an elevated concentration of nitrate extend approximately 250 ft from the edge of the field to the creek. The decrease in concentration of nitrate could result from denitrification, as indicated by the low concentration of dissolved oxygen in water from all wells at the cluster and the excess nitrogen gas in water from well WLC00e. The lowest concentration was in the deepest wells at the cluster, however, indicating that if denitrification occurred, it resulted from organic material deposited with the sediments, not the current presence of the riparian woodland. Although the ground-water-flow paths from the uplands to the creek at the Walls Landing Creek site and the quality of ground water that flowed from the uplands to the creek in the rest of the watershed are not

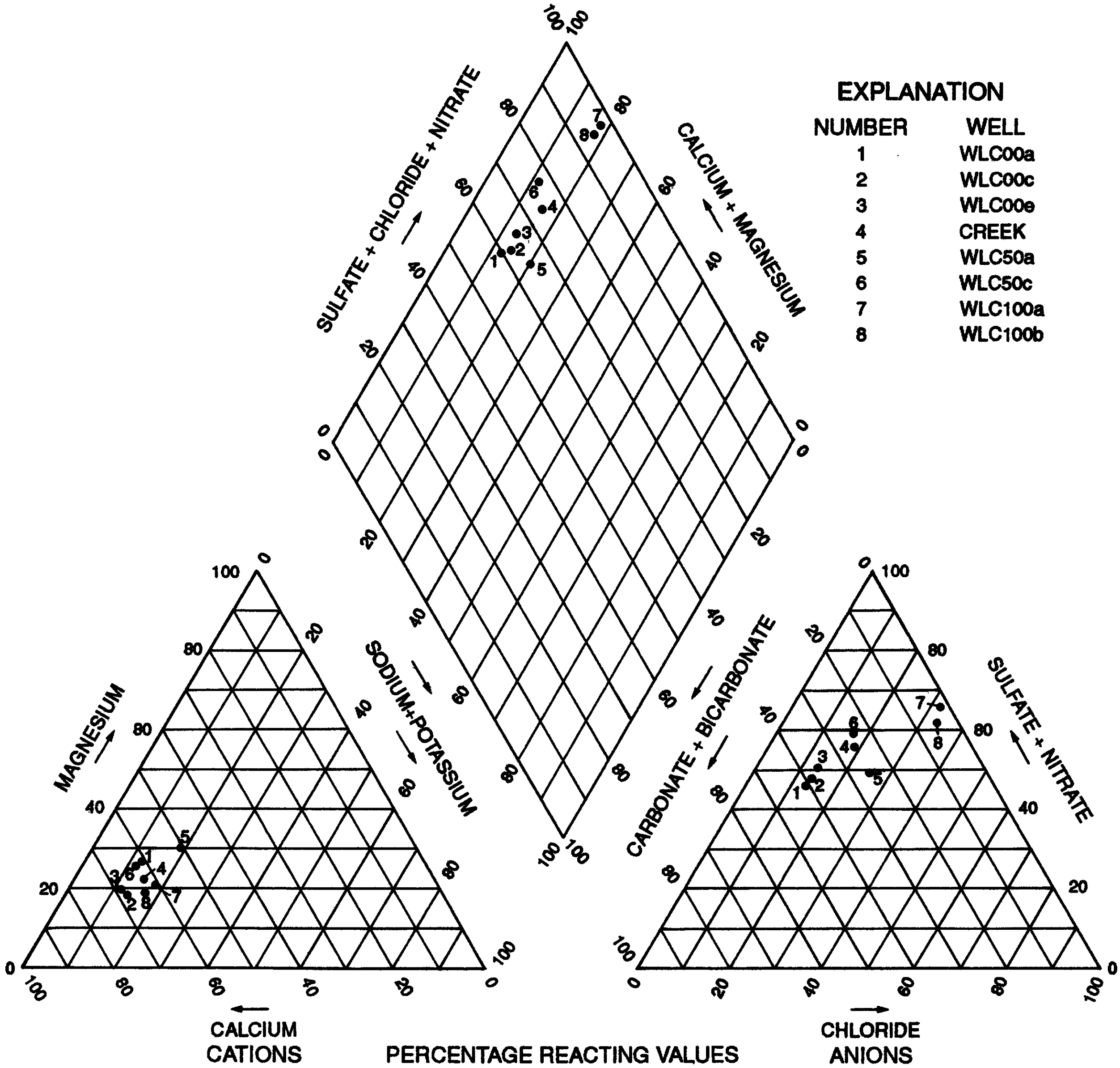


Figure 32. Relative ionic composition of ground water at the site with coarse-grained upland sediments adjacent to a nontidal creek, Eastern Shore, Virginia.

certain, the 3.8 mg/L of nitrate in the creek does not appear to be inconsistent with the concentration of nitrate in ground water at cluster WLC00. On the basis of the land use adjacent to the creek (fig. 7) and the hydrologic processes at the Walls Landing Creek site, a large part of the ground water that discharged to Walls Landing Creek probably was water that infiltrated through the agricultural fields. Thus, the geochemical processes that decreased the concentration of nitrate in the ground water before it discharged to the creek probably prevail along much of the creek.

Implications of the Geohydrology and Geochemistry on Land-Use Management Practices

The geohydrology and geochemistry of the Walls Landing Creek site contrast how riparian woodland and the composition of sediments beneath a riparian woodland can affect the quality and flow of ground water differently. Evapotranspiration by riparian woodland can serve as a discharge and uptake pathway for part of the ground water and nitrate, similar to that observed in the wooded wetland and saltwater marsh transect, however, part of the ground water will flow to the creek and discharge as base flow. Through evapotranspiration and nitrate uptake, riparian woodland can reduce nitrate loads discharged to a creek but can also reduce the amount of ground water discharged to creeks as base flow. Hence, the concentration of ground-water nitrate probably is not affected by this process.

Riparian woodland had little effect on the quality of ground water that flowed from the edge of the field to the creek bank. Changes in ground-water quality primarily resulted from the effects of changes in sediment composition that resulted from the deposition of the sediments, not the current presence of the riparian woodland. Changes in ground-water quality that result from the sediment composition can differ at different creeks and at different locations along a creek as indicated by the change in specific conductance along Walls Landing Creek and the difference between the specific conductance of Walls Landing Creek and the ground water. Although concentrations of dissolved oxygen and nitrate decreased little in the 125 ft between cluster WLC100 and the deepest three wells at cluster WLC50, concentrations decreased substantially in the next 125 ft between clusters WLC50 and WLC00; thus, the distance over which such changes take place and where they take place will depend on the local geohydrology and geochemistry of each system. Such changes can often be expected where local changes in topography reflect possible changes in the composition of the underlying sediments. Thus, both general and specific knowledge of the geohydrology and geochemistry of each local system can help in evaluating how to plan and manage land use in a manner that will reduce loads of nitrate and other contaminants discharged from the ground water to the creeks.

Although the role of riparian woodlands in improving ground-water quality appears to be limited by the geohydrologic and geochemical processes, riparian woodlands can improve water quality. The limited effect of riparian woodlands on ground-water quality does not lessen the importance of riparian woodlands to improve the quality of surface runoff by trapping sediment and removing nutrients. In serving this function, the woodland can also increase ground-water recharge and improve the quality of recharging ground water through such processes as denitrification; however, these effects generally would be limited to water that infiltrated through the woodland and recharged the surficial aquifer. Because the organic content of the deep sediments did not fully denitrify ground-water nitrate, resulting in elevated nitrate in discharge to the creek, limits on residential density and controls on the timing and rate of fertilizer applied could be important in controlling the loads of nitrate discharged to nontidal creeks. The scale of this study did not allow an assessment of the role of riparian soils on possible denitrification or uptake by trees as ground water discharges near the creek bank through adjacent creek bed sediments. This role could be very important but very localized. Like ground water that flows deeper beneath the riparian woodland and flood plain, ground water that flows beneath the root zone at the creek bank probably will not be affected by the riparian woodland.

SUMMARY AND CONCLUSIONS

Ground water discharged from agricultural and residential areas can be a significant source of nitrate to the surface water to which it discharges. Nitrate in ground water that discharges to coastal waters is of concern because an elevated concentration of nitrate can contribute to the eutrophication of the estuaries. Concentrations and loads of nitrate in ground water that discharges to an estuary are affected by various geohydrologic and geochemical processes. These processes are affected by the permeability, mineral content, and organic content of the sediments. These sediments compose areally extensive formations that have regional patterns in grain size and organic and mineral content but also contain local heterogeneities. The permeability, mineral content, and organic content of the sediments result, in part, from the environment in which the sediments were deposited and can be reflected by the topography, hydrology, and land use of today. Knowledge of how these processes affect concentrations and loads of nitrate in ground water discharging to estuaries will help the development of land-use and land-management plans that minimize loads of nitrate discharged to estuaries. Four sites were selected to study the effects of specific geohydrologic and geochemical processes on the concentration of ground-water nitrate in, and near, ground-water-discharge areas on the Eastern Shore, Virginia.

One site is located where precipitation infiltrates through upland agricultural fields primarily underlain by fine-grained, sediments that contain abundant organic material, recharges the surficial aquifer, then discharges to Leatherberry Creek. Local deposits of coarse-grained sediments that contain little organic material border Leatherberry Creek. Ground-water levels indicate the area is poorly drained except near the tidal creeks. Water levels are near or above land surface in many interior areas during the winter. Net recharge rates calculated from chlorofluorocarbon age dating of the ground water were 2.3 in/yr or less through the fine-grained sediments and ranged from 3.2 to 4.4 in/yr through the coarse-grained sediments. In water that infiltrated through fine-grained sediment beneath the fields and recharged the surficial aquifer, the concentration of dissolved oxygen was 1 mg/L, or less, and nitrate was less than the detectable concentration. In ground water from precipitation that infiltrated through coarse-grained sediment beneath the edge of the fields, the concentration of dissolved oxygen ranged from 1.7 to 6.8 mg/L and the concentration of nitrate ranged from 9.9 to 14 mg/L as N. Concentrations of dissolved oxygen and nitrate in ground water that flowed beneath a more than 100- to 150-ft-wide riparian woodland to Leatherberry Creek changed little from those in the source ground water beneath the fields.

A second site next to Cherrystone Inlet is located where precipitation infiltrates through upland agricultural fields underlain by coarse-grained sediments of the Occohannock Member of the Nassawadox Formation containing little organic material. Recharge enters the surficial aquifer before discharging directly to Cherrystone Inlet. This site is underlain by local deposits of fine-grained sediments that overlie the coarse-grained sediments near part of the discharge area. The fine-grained sediments are up to 12 ft thick and may have been deposited throughout the bottom of Cherrystone Inlet and adjacent near-shore areas during previous high stands of the sea. The fine-grained sediments appear to have been eroded along parts of the shore, where coarse-grained sediments directly border the estuary. Specific conductance of the ground water and comments by local residents indicate that unusually high tides periodically inundate and recharge the fine-grained sediments. Ground-water levels and specific conductance indicate that ground water discharges readily where coarse-grained sediments are adjacent to the estuary, but ground water discharges more diffusely through the fine-grained sediments, resulting in sluggish ground-water flow through, and slow flushing of the salty water from, the fine-grained sediments. Seasonal changes in vertical hydraulic gradients indicate that ground water also discharged by evapotranspiration to the riparian woodland overlying the fine-grained sediments.

The concentration of dissolved oxygen ranged from 5.4 to 8.0 mg/L in ground water nearest the water table beneath the upland fields and generally decreased with depth and age of the water. The concentration of nitrate ranged from 0.13 to 27 mg/L as N. The lowest concentration of nitrate was in ground water in, and beneath, the fine-grained sediments, and the concentration of nitrate was elevated in ground water in the coarse-grained sediments adjacent to the estuary. The reduced concentration of nitrate appears to result from a combination of dilution with salty water having little nitrate and denitrification caused by the relatively greater amounts of organic material that were deposited with the sediments, and not the current presence of the riparian woodland.

A third site is located where precipitation infiltrates through upland agricultural fields underlain by coarse-grained sediments of the Joynes Neck Sand and the Butlers Bluff Member of the Nassawadox Formation containing little organic material and recharges the surficial aquifer before discharging to a wooded wetland adjacent to a saltwater marsh and Magothy Bay. The wooded wetland and saltwater marsh are in lowlands underlain by a mixture of fine-grained and coarse-grained sediments of the Wachapreague Formation with variable organic content. Ground water flows from the upland fields toward the wetlands and saltwater marsh. Ground-water-recharge rates estimated from the age of the ground water ranged from 2.7 to 13.3 in/yr with a median of 9.6 in/yr. Changes in horizontal and vertical hydraulic gradients, the saturated thickness of the surficial aquifer, and ground-water quality, and the presence of daily cycles in ground-water levels, indicate that most of the ground water that flowed from the upland fields through the surficial aquifer discharged to the wooded wetlands, primarily within the first 850 to 1,200 ft of the wetlands. Much of the ground water appears to discharge by evapotranspiration; an estimated 10.9 to 37.6 in. of ground water discharged during the period from June 2, 1993 through August 31, 1993. Salty water from salt spray and inundation during unusually high tides has recharged the surficial aquifer in the part of the wetlands toward Magothy Bay. Ground water appears to discharge from the underlying confined aquifer to replace ground water from the uplands that flows through the surficial aquifer and discharges to the wetlands.

Ground-water quality at this site can be classified as agriculturally affected water, water discharged from the confined aquifer, salty water, or mixtures of these types. Agriculturally affected water consists of precipitation that infiltrated through the agricultural fields, or runoff from the fields that infiltrated through woodland soils adjacent to the fields. Concentrations of nitrate and other constituents were elevated in the agriculturally affected water. As agriculturally affected ground water flowed through sediments of the Wachapreague Formation, increases in the organic content of sediment decreased the concentration of dissolved oxygen to less than 1 mg/L. Changes in the organic content of sediment result from deposition in a beach ridge, cuspate spit, and lagoonal environment (Mixon, 1985), not the current presence of riparian vegetation. The concentration of nitrate in agriculturally affected water having a concentration of dissolved oxygen exceeding 1 mg/L ranged from 7.8 to 22 mg/L as N. The concentration of nitrate was less in water that infiltrated through woodland areas than through the upland fields. The concentration of nitrate decreased beneath the wetland, but a concentration exceeding 2.5 mg/L as N extended into the woodland more than 500 ft; a concentration exceeding 1 mg/L as N extended more than 650 ft into the woodland. It appears that most, if not all, of the agriculturally affected ground water discharged to the first 850 to 1,200 ft of the woodland, probably as evapotranspiration.

The fourth site is located where precipitation infiltrates though upland agricultural fields underlain by coarse-grained sediments of the Joynes Neck Sand that contain little organic material and recharges the surficial aquifer before it discharges to Walls Landing Creek, a nontidal creek. The flood plain of the creek contains a riparian woodland and appears to be underlain by sediments that contain a mineral and organic content different from that of sediment underlying the uplands. Horizontal hydraulic gradients indicate that the watershed from which ground water flowed toward Walls Landing Creek was small. Vertical hydraulic gradients and standing water indicate that ground water seasonally discharged to land surface in the first part of the riparian woodland, but much of the ground water probably discharged to the creek.

The mineral content of the sediments that underlie the riparian woodland appears to differ from that beneath the upland fields because concentrations of many major ions in the ground water increased between the field and the creek. These differences in the mineral content of the sediment appear to be accompanied by changes in the organic content that also affect concentrations of dissolved oxygen and nitrate. The concentration of dissolved oxygen in the surficial aquifer ranged from 3.8 to 9.0 mg/L beneath the fields and the edge of the fields and changed little as ground water flowed halfway from the fields toward the creek beneath the riparian woodland (at cluster WLC50 about 125 ft from the field) but decreased from about 5.0 to 1.0 mg/L, or less, as the ground water flowed the remaining 125 ft toward the creek.

The concentration of nitrate beneath the field and the edge of the field ranged from 6.6 to 21 mg/L as N. The concentration of nitrate at cluster WLC50 (except for water from well WLC50a) was similar to that beneath the fields and the edge of the fields (ranging from 9.7 to 14 mg/L as N). The concentration of nitrate decreased to a range of less than the detectable concentration to 6.0 mg/L as N at the bank of the creek. The decrease in concentration of nitrate appears to result from denitrification, as indicated by the presence of 11.4 mg/L of excess nitrogen gas in water from well WLC00e and because of the depth of the well. Changes in the organic content of the sediment appear to result from the depositional environment of the sediments and not from the current presence of riparian woodlands because the organic material appears to be evenly spread through the sediment rather than around live, dead, or decaying roots.

Observations made at these sites can have important implications for land-use planning and management to minimize discharge of nitrate from ground water to estuaries and other surface waters. Many implications can apply beyond the particular land use, contaminant, or geohydrologic and geochemical environments that were studied. The effects observed on nitrate beneath agricultural fields would be similar to the effects on nitrate beneath residential areas and other land uses in similar geohydrologic and geochemical environments. Geochemical environments can affect other contaminants differently, but in a predictable manner, depending on how the decomposition and mobilization of a contaminant or the affinity of the contaminant for sediments is affected by presence or absence of dissolved oxygen. The low concentration of nitrate in ground water beneath agricultural fields underlain by fine-grained sediments of the Kent Island Formation that contain abundant organic material can be expected in other systems with similar sediment composition in the recharge area. Effects of coarse-grained sediments that contain little organic material in other systems throughout the Eastern Shore and elsewhere could be similar to those observed in this study. Where ground water flows from coarse-grained sediments that contain little organic material to fine-grained sediments with a greater organic content (such as where ground water flows from the Joynes Neck Sand to the Wachapreague Formation, or where local heterogeneities are present, such as at Cherrystone Inlet), nitrate can be denitrified, resulting in a reduction of nitrate loads that discharge to surface waters.

Differences in sediment composition, as affected by depositional environment, can also affect the hydrology. Extensive areas of fine-grained sediments in recharge areas, such as at Leatherberry Creek, can cause poor drainage and result in low rates of ground-water recharge. The local presence of coarse-grained sediments overlain by fine-grained sediments, such as at Cherrystone Inlet, can diffuse the discharge of ground water over a large area. Decreases in saturated thickness of the surficial aquifer because of changes in sediment composition, such as at the wooded wetland and saltwater marsh site, can cause ground water to discharge to land surface. Where land surface is low and flat, hydraulic gradients will be low, also causing ground water to discharge to land surface.

Riparian woodlands appear to have little effect on the concentration of nitrate in the ground water that flows from beneath agricultural fields into the woodlands; however, riparian woodlands improve the quality of surface runoff from fields. Additionally, nitrate in surface runoff from fields can denitrify as the runoff infiltrates through the woodland soils and recharges the ground water. Denitrification as ground water discharges to the surface through woodland soils can also reduce the concentration of nitrate. Riparian woodlands can also provide a pathway for ground-water discharge through evapotranspiration. This discharge pathway reduces the loads of nitrate and the amount of fresh water discharged to an estuary and can be an important mechanism for limiting the amount of nitrate discharged to an estuary. Although riparian woodlands do not affect the concentration of nitrate in ground water that flows from the fields, removal of sediment and nutrients from surface runoff, denitrification of runoff that recharges through woodland soils, denitrification in discharging ground water, and evapotranspiration are important functions of woodlands in protecting the quality of surface waters.

Discharge of contaminants through the ground water can be affected by alterations in the ground-water flow in the wetlands; ditches in a wetland can provide a short-circuit pathway for discharging ground water to reach an estuary, and cutting trees in, and near, a wetland can reduce the rate of evapotranspiration and increase the rate of runoff of ground water that discharges to an estuary. Consequently, the types of land use and how the land is managed in a particular geohydrologic and geochemical environment can affect the transport, retention, or geochemical alteration of potential contaminants, and how they discharge through the ground water to coastal waters.

Spatial differences in the geohydrology and geochemistry of an area can determine how land use affects the concentration of nitrate in ground water. The spatial differences in the ground-water flow and chemistry result from horizontal and vertical trends in the organic content of the sediments and the grain size of the sediments. The width of an area needed for geohydrologic and geochemical processes to eliminate or sufficiently reduce nitrate in ground-water discharge depends on the particular system; thus, an area can be better protected when more is known about the particular system. These study sites showed that ground water having an elevated nitrate concentration flowed more than 850 ft beneath a wooded wetland. This is a much longer flow path for ground water containing an elevated concentration of nitrate than is commonly reported. By incorporating the knowledge of the local geohydrologic and geochemical processes in land-use planning and management practices, loads of ground-water nitrate discharged to an estuary can be minimized.

Where geohydrologic and geochemical processes do not significantly limit loads of nitrate that leach into the ground water and discharge from ground water to surface waters, zoning and land-use management practices such as implementing cropping practices that minimize nitrate leaching are important for reducing the loads of nitrate discharged to surface waters. For residential wastewater disposal, this could include the use of low-density residential development to reduce the nitrate loading from septic tanks, or centralized wastewater-treatment systems to remove nutrients from the water before it discharges. The rate and timing of fertilizer application can affect the amount of nitrate that leaches into the ground water. Cover crops can potentially remove excess nitrate from fertilizer application and nitrate from the decomposition of crop residue to limit leaching. Where geohydrologic and geochemical processes can limit the leaching of, or remove, nitrate by denitrification or plant uptake after it has leached into the ground water, loads of nitrate discharged to the surface water will be small even when residential densities are great and abundant nitrate is available from fertilizer application. Crops for which recommended timing and rates of fertilizer application leach large quantities of nitrate can be raised without contributing significant loads of nitrate discharged to surface waters through the ground water where geohydrologic and geochemical processes naturally reduce nitrate loads. Research into the effects of the timing and rates of fertilizer application and the use of cover crops on crop yield and the leaching of nitrate into the ground water can help to reduce loads of nitrate discharged from the ground water into surface waters.

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